SUMMARY OF PERTINENT BIOLOGICAL CHARACTERISTICS OF POTENTIAL OCEAN THERMAL ENERGY CONVERSION (OTEC) SITES IN THE PACIFIC OCEAN

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I. INTRODUCTION

The oil crisis of 1973-74 sparked a movement among many oil-dependent nations of the world to look at alternative forms of energy to satisfy their energy needs. Particularly vulnerable were isolated island communities that relied heavily on imported oil for their energy needs. As oil grew progressively costly, island governments exerted greater effort to conserve and to look for other affordable sources of energy.

Among alternative sources considered suitable were direct solar radiation, wind, biomass, and ocean thermal energy. All are renewable and presumably nonpolluting compared with oil, coal, and nuclear energy.

Among them, the ocean offers a tremendous potential as an energy source. Ocean thermal energy conversion (OTEC), a technique for tapping incoming solar energy stored in the surface layers of tropical and subtropical oceans, is a promising technology that is particularly useful to a large number of island governments and developing nations. Because the ocean thermal energy resource lies primarily within the 20° latitudinal bands, developing countries that lie within or near these boundaries can exploit OTEC in their contiguous territorial seas.

This report synthesizes existing historical information that has pertinence to representative land-based and plant ship OTEC sites in the Pacific Ocean. It provides the basis for extrapolating environmental information to probable OTEC operating conditions so that the potential risk of such facilities to existing fisheries and other marine resources can be evaluated.

A. Overview

In 1 hour the world's oceans receive enough solar energy theoretically to meet its annual demand for fuel. Solar radiation is greatest just beneath the sun and decreases as we move away from that point (Gross 1972). Averaged over a year, the maximum amount of solar energy is absorbed in the low-latitude tropical region. The result is that the Earth receives most of its heat between lat. 40°N and 40°S, whereas there is a net loss in the high latitudes between 40° and 90° in both hemispheres. The heat transfer from low to high latitudes in the ocean and atmosphere functions as simple heat engines. The transformation of some of the ocean's heat energy into mechanical energy is in the form of waves, currents, and winds. A large proportion of the solar energy, however, is simply stored in the warm tropical waters. Tapping this stored energy with OTEC can produce electrical energy, which is currently produced by other fuel and technologies including oil, coal, nuclear power, and hydropower, as well as energy intensive products such as hydrogen, ammonia, and aluminum. An important by-product of some OTEC system design is fresh water.

The OTEC relies primarily on the temperature difference between the warm surface and cold deep waters of the oceans. Warm water drawn from the ocean's surface provides heat which is transferred through a heat exchanger to a working fluid. Enclosed in a partial vacuum, the working fluid is evaporated by the heat and the resulting high-pressure vapor drives a

turbine to produce electricity. Cold water is then pumped from the deep layers to condense the low-pressure vapor in a second heat exchanger. The working fluid is then pumped back and recycled.

B. Potential Areas

Although the ocean thermal resource needed for OTEC can be found year round in the tropics between lat. 20°N and 20°S, achieving maximum efficiency from an OTEC plant would require certain characteristics for optimal deployment. Among these are the bottom topography and profile, temperature difference between the warm surface and cold deep water, sub-strate, permanent water flow, currents (tidal, wind-driven, and inertial), mass transport by waves, climatic conditions, benthic properties, and chemical properties of the sea water.

1. Temperature and depth requirements

Site selection is very critical to the development of an OTEC plant. The magnitude of the temperature change (ΔT) between the warm surface layer and the cold deep layer must be sufficiently large to maintain power plant output and efficiency. An operational minimum ΔT of $19C^o$[1] is essential (Haven 1981), and an annual minimum temperature difference of at least $20C^o$ between surface and deep-ocean waters is necessary (Sullivan et al. 1981). The mixed layer not only must be sufficiently deep to ensure that the warm-water resource is available at the intake depth but also is a consideration in calculating the discharge depth at which recirculation is kept to a minimum.

The ocean thermal resource for OTEC is enormous even if only areas with ΔT of at least $19C^o$ are considered (Yuen 1981). The depth requirement for a potential OTEC site will vary depending on the geographical location of the plant. For example, at Kahe Point, Oahu, the water at 500 m is about $18C^o$ colder than surface water whereas at 1,000 m the water is colder than surface water by about $20-22C^o$. On the other hand, ΔT of $19C^o$ can be maintained at only 457 m in waters off Guam.

Figures 1 and 2 show ΔT between the surface and 1,000 m for the world's oceans between lat. 40°N and 40°S (U.S. Department of Commerce 1980).

2. Economic resource zone boundaries

The 200-mile economic zones of countries in the Pacific Basin and around the rim are shown in Figure 3. Economic zones of adjacent countries within many parts of the South Pacific are not well established. Except where grazing plant ships would be operating in open water, it is not anticipated that boundary disputes will occur, because most plant designs under consideration involve shoreside facilities or nearshore towers.

C. Predicted Sites

Several sites in the Pacific have been studied for possible land-based OTEC facilities, including Keahole Point and Kahe Point in the Hawaiian

Islands, Cabras Island off Guam, Japan, Manila in the Philippines, the Republic of Nauru, Taiwan, Mexico, French Polynesia, and New Caledonia.

1. French Polynesia and New Caledonia

French Polynesia and New Caledonia are considered potential OTEC sites in the South Pacific (Yuen 1981). Results of a study by the Centre National pour l'Exploitation des Oceans (CNEXO) indicated that an offshore plant of 3-15 MW is feasible in waters close to Tahiti. With costs about equal for both an open- and closed-cycle system,[2] CNEXO favors the former because of the added advantage of fresh-water production. A small-scale OTEC plant is also economically competitive with oil-fired plants in tropical islands (Marshand 1979, 1980).

2. Guam

The existence of ideal oceanographic conditions such as consistently warm surface water and a steep submarine slope close to shore makes OTEC a viable alternative for energy in Guam. Lassuy (1979), demonstrated a consistent annual mean ΔT difference of $23.4C^o$ between the surface and depths of about 854-915 m near Cabras Island and Luminao Reef (Figure 4) and that this ΔT could be obtained only 1.75 km offshore from the Glass Breakwater at the western tip of Luminao Reef.

A review of the oceanographic information from Guam, showed that the temperature difference resource near Guam is unsurpassed among 10 other sites examined throughout the world (Wolff 1979a, Tables 1 and 2). Wolff found mean monthly surface temperatures consistently high year round, ranging between 27.7^o and 29.2^oC. Likewise, consistently large and stable ΔT values were available through the year; an annual average ΔT greater than $20C^o$ is available at depths of slightly less than 500 m.

The major obstacle to OTEC development at Guam is the frequency of typhoons and tropical storms. Seismic activity in the Guam area also poses a threat to OTEC operations. Wolff added that ocean currents near Guam were generally moderate in strength and varied only slightly in direction.

3. Hawaiian Islands

Hawaii, which is located in the northern limit of the Pacific tropical water mass where the temperature difference between surface and deep water is sufficiently large to support OTEC operations, has a steady accessible thermal resource at or greater than $19C^o$ (Haven 1981). Long-term surveys of physical oceanographic conditions and ocean bathymetry around Hawaii revealed that at a depth of 500 m, the waters were typically about $18C^o$ colder than surface water whereas at 1,000 m, the ΔT values increased to $20-22C^o$. The maximum obtainable differences were $24C^o$ at 500 m and $26C^o$ at 1,000 m.

Haven reported that although the thermal profiles for most sites studied in Hawaiian waters showed very similar temperature gradients and seasonal shifts, long-term thermal measurements showed a substantial

surface temperature variation over time. For example, surface temperatures averaged only 22.8°C in 1930. A return to sea conditions responsible for this low temperature could have a disastrous impact on OTEC operations.

According to Haven, the appropriate annual mean temperatures for OTEC operations in Hawaii should be 25°C $\pm$ 1.2°C for surface waters and a constant temperature of 4.5°C at 800 m. These design temperatures should produce a usable thermal gradient of 19.2-21.7C° over the year.

Surface temperatures ranged from 24.7° to 27.1°C at Keahole Point (Bathen 1975). Below the mixed layer, which was 80-100 m thick, temperatures decreased rapidly for another 200 m and only slightly from 330 to 350 m. At 550 m, the temperature was 6.9°C; thus a ΔT of 18.8C° was possible at 550 m. Bathen noted that an annual thermal difference of 18-20C° was typical in the Keahole region. The minimum temperature difference at 610 m was 20.6C° in summer and 18.2C° in winter.

Currents ranged from 0.05 to 0.6 knot off Keahole and speeds of 0.1-0.3 knot were rather typical. The net surface transport was north to northeast in winter (November-May) and a north to south transport (tidal) was more apparent in late summer, although the net drift remained northerly.

Off Keahole, the nearshore slope is steep: It is 610 m deep about 0.8 nmi from shore. The maximum recorded wave height was 1.8 m with a period of 14 sec; however, waves were below 1.2 m about 97% of the time. Bathen predicted the maximum significant wave height for this location to be about 6 m.

Climatic conditions in the Keahole area were generally mild. Winds blew onshore during the day and offshore at night, and rarely exceeded 5 knots. During infrequent storms, wind speeds of 15-30 knots can be expected.

At Kahe Point on the western shore of Oahu, the 1,000-m contour is about 3.8 nmi from shore. The minimum ΔT observed at this site was 20.0C° whereas the maximum reached 22.8C° (Ocean Data System, Inc. (ODSI) 1977). Studies by Seckel (1955) and Maynard et al. (1975) indicate that a minimum of 914 m will be needed to obtain a ΔT of 19C° during winter when surface temperatures are colder. In summer, the temperature difference between the surface and 914 m ranged to 23.0C°.

The depth of the mixed layer at Kahe Point was 50 m in summer and 90 m in winter (ODSI 1977). The upper water column off Kahe exhibited what appeared to be some seasonal variation in current speed whereas in waters deeper than 350 m, there was no evidence of seasonal trend (Noda and Associates 1982). At 50 m, the monthly maximum current speed ranged from 52.7 cm/sec in August to 77.4 cm/sec in May (Noda 1981). Monthly mean values at this depth varied from 17.5 cm/sec in August to 27.2 cm/sec in March.

Currents are often strong off Kahe but could be highly variable (Bathen 1978). The net drift is rather consistent and moderate to strong

toward the south of Maili Point to Barbers Point from August to January when winds are less dominated by the northeast trades. In deep water, net drift is variable toward the shoreline from February to April and directly offshore from May to July.

Waves impinging on the Kahe area may be generated either from earthquakes (tsunami) or wind. An OTEC power transmission cable would require adequate tsunami protection through the coastal zone. Runup or vertical height change during a tsunami at both Kahe and Barbers Point was about 3.6 m during the 1946 tsunami that washed the shores of Oahu (Cox and Mink 1963; Dames & Moore 1970; Armstrong 1973).

In Hawaiian waters, there are a number of sites that satisfy criteria for both nearshore floating and shore-based OTEC power plants. Shupe (1982) identified several locations throughout the state that have some potential for OTEC systems, but reported that additional bathymetric and ocean current studies are needed to verify these sites as suitable. Based on his findings, these areas are:

o Hawaii--Off Leleiwi Point southward to Cape Kumukahi and along the southeastern coast to Ka Lae, then northward along the southwestern and western coasts as far as Keahole Point.

o Maui--Off Hana; also along the southeastern coast from about Kipahulu to Kiakeana Point.

o Molokai--Off Makanalua Peninsula.

o Oahu--Along the Waianae coast from Barbers Point to Kaena Point.

o Kauai--Off the north shore between Hanalei and Kilauea Point; also along the eastern and southern coasts from Wailua to Waimea.

4. Japan

Although the Japanese islands are well north of lat. 20°N and outside the tropical zone where the ocean thermal resources can be found year round, they are strategically located, because the Kuroshio constantly brings a large amount of thermal energy in the form of warm surface water from the tropics.

Oceanographic studies indicate that the Pacific coast of Japan is bathed by the Kuroshio which brings sufficiently warm surface temperature (28°C) and has cold water that can be obtained from 790-m for the needed ΔT.

Homma et al. (1979) considered five sites for OTEC development off Japan. These were at Iriomote Island, Okinawa Island, Toyama Bay, Osumi Islands, and the Izu Peninsula. Data collected from four of the sites showed maximum wind velocity ranging from 39.6 to 78.6 m/sec, significant wave height varying between 8.5 and 15.0 m, and frequency of typhoons ranging from 21-40 times/year at Toyama to 41-60 times/year at Iriomote, Okinawa, and Osumi. They concluded from their studies that Osumi and

Toyama would be most suitable as representative sites for OTEC development in Japan.

Homma et al. reported that the temperature profile at Osumi was quite different from that at Toyama. At 500 m, the temperature at Osumi reached 9.18°C whereas at Toyama, it was 0.35°C. The optimum cold-water intake depth was determined to be 790 m at Osumi and 370 m at Toyama. Minimum and maximum mean surface temperatures 1,000 m off Osumi and Toyama are shown in Figure 5.

In addition to developing OTEC facilities to satisfy their own power needs, the Japanese are also vitally cognizant of the market in technology transfer, particularly along oil-dependent Pacific islands where ΔT's are excellent all year long and deep cold water is available nearshore. In 1979, Tokyo Electric Power Services Company, Ltd. began work on a 100 kW "experimental confirmation" closed cycle plant sited on the island of Nauru. This plant was a research facility for testing heat exchangers (H. Pennington, DPED, pers. commun., September 15, 1982).

5. Manila, Philippine Islands

Historical oceanographic data indicate that in waters off Manila, Philippine Islands, an excellent thermal difference exists between surface and deep water to make OTEC development feasible (Wolff 1979b). Between lat. 14°–16°N and long. 118°–120°E off the west coast of Luzon, surface temperatures were high throughout the year and the lowest monthly mean was about 27.2°C. The monthly mean ΔT was 24.0C° at 1,000 m, and annual mean thermal difference was 20.0C° at 500 m. It was concluded from the study that the thermal difference at 500 m was sufficiently large and that the cold water pipe for the plant could be made relatively short.

Wolff found that the continental slope off the Philippines was steep and that the 1,000-m contour lay within 10 nmi off the shoreline around Luzon. The single most important obstacle to OTEC development was climatic conditions, that is, typhoons, high winds, and storms were a major problem in this area. In addition, seismic activity could create further concerns.

Water currents around the islands were generally moderate with some variation during the year. Also, the mixed layer appeared to be adequate throughout the year.

6. Mexico, west coast

A study of a site chosen for possible OTEC development off the west coast of Mexico showed that the temperature difference was more than adequate for potential use (Wolff 1979d). The site (between lat. 20°–23°N and long. 105°–110°W), had an annual mean ΔT of 20.0C° at 800 m and 20.9C° at 1,000 m. During March, the coldest month of the year, the mean ΔT was 17.2C°. Wolff reported that at 800 m, there was some variation in monthly mean temperature difference; however, this difference was adequate even in the coldest month (Tables 1 and 2).

The relatively shallow mixed layer in this area was persistent throughout the year. Surface currents were weak with some variation in the direction of the flow. Because of the existence of a large continental shelf, the distance from shore to the 1,000-m depth contour was relatively great although one bay nearby could supply cold deep water within 2.7 nmi from the site.

Storms could be a major problem in this area from May to November; sea conditions and swells were moderate and did not appear to be of major concern.

7. Pacific plant ship

A plant ship is a self-propelled surface platform which can cruise to areas where ΔT is greatest and storms less severe so that OTEC power can be used to produce a storable energy-intensive product or other commercial products such as ammonia, hydrogen, methyl alcohol, liquid natural gas, aluminum, alloys prepared in electric furnaces, semiconductor materials, and to refine manganese nodules (Avery 1980). Proximity to shore and power grids is not an important consideration for a plant ship compared with land-based or bottom-mounted plants. Furthermore, distance to shore is a minor consideration and there is no need for submarine cables to transmit electricity. Although information on bottom topography is not crucial, it is necessary that there be sufficient depth to provide the cold water needed.

The site examined for plant ship operation was located near the approximate limits of the North Equatorial Current and the Pacific Equatorial Countercurrent (between lat. 5°-10^oN and long. 90°-95^oW). Wolff (1979c) described this area as excellent for potential OTEC use. He found surface temperature consistently high, ranging from 26.5^o to 28.5^oC, and an annual mean ΔT greater than $20C^o$ at a depth of 550 m or greater (Tables 1 and 2).

For the entire plant ship region studied, Wolff found bottom depths much greater than 1,500 m. The depth of the mixed layer was very shallow year round but also nearly nonexistent at times, indicating that a warm-water intake could be located (or positioned) very near the surface. Storms and high winds were not a major problem for this site partly as a result of its proximity to the Equator. Compared with other Pacific sites examined, mean surface currents were somewhat larger in magnitude. Wolff concluded that current shears may be troublesome in this area.

8. Taiwan

Like Japan, Taiwan is also situated within the influence of the Kuroshio, thus making it possible to consider OTEC. Along the east coast of Taiwan, the Kuroshio flows close by and the 1,000-m depth contour is relatively close to shore. Liang et al. (1980) found that the ΔT of $20C^o$ occurred at about 500-550 m in May-October in waters off Hualien (Figure 6). The mixed layer off Taiwan was usually 20 m thick in the summer but as much as 60 m in the winter. Frequently, no mixed layer existed at other times of the year. Liang et al. concluded that the water off Taiwan was

highly stratified; therefore, they recommended that the warm-water intake
for any OTEC plant be located near the sea surface. They further
recommended that because of the hazards from a typhoon, any OTEC plant
built in Taiwan should be a shelf-mounted facility.

In a second study, Liang et al. (1981) examined a site further south
along the eastern and western coasts of southern Taiwan. Data were
gathered for 6 months at a depth of 300 m off Hung-tzai (Figure 6). Their
study demonstrated that by utilizing an existing nuclear power plant's
discharged cooling water, which was about $10C^o$ higher than ambient water,
it would be possible to attain a ΔT of 21°-25^oC. Other results indicated
that the mixed layer is not detectable in summer and that the thermocline
generally extended to 200 m. They concluded that from the standpoint of
ocean engineering, Hung-tzai was ideal for a land-based OTEC plant coupled
to a power plant.

II.   PHYTOPLANKTON

Ranging in size from about 1 µ to 1 mm, marine phytoplankton include
representatives of many algal groups. These free-floating algae build up
protoplasm and food reserves directly from carbon dioxide and nutrient
salts and form the base upon which the rest of the marine food chain
depends (Newell and Newell 1963; Sullivan et al. 1981). Although most
bacteria are heterotrophic, they are not included in the phytoplankton
because of their ability to absorb organic nutrients directly from the
external medium.

Because the effects of OTEC on the marine environment are likely to be
seen initially in changes in the phytoplankton, due in part to the
discharge of cold, nutrient-rich deep water into the photic zone, any
shifts that occur in standing stock, community structure, or photosynthetic
activity of the phytoplankton carry implications for the entire trophic
community (Noda et al. 1981b).

The standing stock and primary productivity of phytoplankton are
usually determined by assessing chlorophyll a, phaeopigments, adenosine
triphosphate (ATP), and photosynthetic rate (Noda et al. 1981b).
Chlorophyll a values are universally accepted as a measure of phytoplankton
biomass whereas phaeopigment values, obtained in the process of adjusting
the accuracy of chlorophyll a values, also provide physiological and
ecological indices of community status. The ATP values give a measure of
total biomass which embraces not only phytoplankton but also bacteria and
microherbivores. Photosynthetic rate is essentially a measure of primary
productivity and represents the primary input of chemical energy into the
marine food web.

A.   Open Ocean Sites

Because OTEC-1 experiments were carried out aboard the Ocean Energy
Converter (OEC) anchored offshore in the Keahole Point area, data gathered
from these experiments can be used to depict ecosystem functions at open
ocean sites. The following discussion revolves around some of the results

obtained from these experiments and the results of the Deep Ocean Mining
Environmental Study (DOMES) that are pertinent to this report.

1. Biomass, primary productivity levels, compensation depth

1.1 Biomass

Simply defined, biomass is the amount of living matter per unit of
water surface or volume and is used as an index of standing stock. Typical
units for standing stock measurements are μg/liter, mg/m^3, g/m^2, and kg/ha.
Additionally, phytoplankton standing stock may be described as consisting
of 10^6 cells/liter of a species, or being represented by a chlorophyll a
concentration expressed as mg/m^3 (Parsons and Takahashi 1973).

In a study to evaluate the variability in physical, chemical, and
biological parameters at an open ocean site off Keahole Point, Hawaii, at
lat. 19°55'N and long. 156°10'W in waters 1,300-m deep (Figure 7), Noda et
al. (1980) conducted six cruises (HOTEC-1 through HOTEC-6) to examine an
OTEC benchmark site. They found a surface mixed layer of relatively low
chlorophyll a concentrations, ranging between 0.03 and 0.18 mg/m^3. As is
typical of other oceanic water columns from many regions of the world's
oceans, a subsurface chlorophyll maximum was also present below which
values declined to negligible levels. Among the explanations offered for
the presence of the deep chlorophyll maximum were:

o Decrease in phytoplankton sinking rate.

o Increase in cellular content of chlorophyll via adaptation to
    reduced light levels.

Noda et al. (1980) reported that the subsurface chlorophyll maximum
was located between 64 and 94 m and ranged from 0.17 to 0.62 mg/m^3 (Figure
8). Temporal variability in phytoplankton stock was demonstrated by
comparing the integrated levels. Within the mixed layer, integrated
chlorophyll values were 1.93-10.30 mg/m^2 compared with 13.77-45.13 mg/m^2
for the entire upper 260 m. Noda et al. found no correlation between
variations in the standing stock of phytoplankton and variations in any of
the other parameters measured.

Phaeopigment values are usually of importance in adjusting chlorophyll
measurements for possible contamination (Shuman and Lorenzen 1975). The
phaeopigment profile at Keahole paralleled the shape of the chlorophyll
profile; concentrations were usually one-third to one-half the chlorophyll
levels, except in the region of the pigment maximum where phaeopigment
concentrations increased to 80-90% of the chlorophyll levels (Bienfang
1977). Noda et al. (1980) found a similar distribution of phaeopigments
where the vertical structure was similar to that of chlorophyll. Over six
cruises, the shape of the vertical profile was similar; however, the
phaeopigment levels varied widely from undetectable levels to 0.09 mg/m^3
within the mixed layer, from 0.05 to 0.45 mg/m^3 at the subsurface maximum
level, and from 3.67 to 22.53 mg/m^3 integrated over the entire upper 260 m.

Noda et al. (1980) also noted that the depth of the phaeopigment maximum was at or below that of the chlorophyll maximum. They reasoned that this difference may be attributed to photo-oxidation of the light-labile phaeopigments and to phaeopigment production in a region where low light levels inhibit phaeopigment degradation and chlorophyll production.

Noda et al. (1980) also used ATP values as a total microbial biomass indicator for offshore waters off Keahole Point. They found that the ATP values generally decreased with depth. In the surface layers (0-100 m), values were highly variable ranging from 2.37 to 52.72 $\mu g/m^3$. They found no indication of a subsurface maximum as was apparent for chlorophyll a and phaeopigment concentrations. Depth-integrated ATP values varied from 0.56 to 5.72 mg/m^2 over 12 hydrocasts. The average over six cruises was 3.00 ± 1.78 (s.d.) mg/m^2.

The ATP method, one of several biochemical techniques used to estimate microbial biomass, measures the biomass of total microplankton including phytoplankton. Sorokin (1981) has reported that ATP values may be difficult to interpret and may exceed the real microbial biomass by 1.5 to 4.0 times. Nevertheless, empirical correlations have been found for some oceanic habitat thereby making the method useful.

Noda et al. (1980) also used the production/biomass (P/B) ratio expressed as mg carbon/mg chlorophyll a/h (Bienfang and Gundersen 1977) as an indicator of the specific rate of activity of each biomass unit. Primary productivity values represent the rate at which phytoplankton are performing work or putting energy into the trophic system whereas chlorophyll a values represent the component of the population performing that work. For data from six cruises P/B ratios varied from 0 to 8.31 mgC/mg chlorophyll a/h. Noda et al. found that the P/B ratio varied vertically and temporally. Vertically, P/B ratios from all cruises rapidly declined with depth which indicated a diminishing availability of light for photosynthesis. Temporally, the range of P/B ratios over the water column for each of the six cruises were as follows: 0.72-4.57; 0-2.80; 0-2.27; 0.03-0.52; 0.32-8.35; and 0-1.11 mgC/mg chlorophyll a/h. Almost all the values, particularly those from near surface samples demonstrated strong nutrient impoverishment.

In a study in the DOMES area of the tropical Pacific (Figure 9), El-Sayed and Taguchi (1979) found that the water in this region (lat. 5°-20°N and long. 128°-155°W) was characterized by low chlorophyll a values, a condition normally expected for oligotrophic tropical and subtropical oceanic waters. The surface chlorophyll a values averaged 0.117 mg/m^3 whereas the value integrated through the water column (to the bottom of the euphotic zone) averaged only 19.6 mg/m^2. Also, a subsurface chlorophyll a maximum layer (CML) was characteristic of the area studied and the CML was found deeper in summer (69 ± 24 m) than in winter (54 ± 30 m). The chlorophyll a value was high below the euphotic zone and contributed about 20% of the chlorophyll in the water column in summer and winter. The data suggested that the CML results either from grazing by zooplankters or from slower growth of larger phytoplankton cells (Figures 10 and 11).

El-Sayed and Taguchi reported that in summer the CML was either in the middle or at the bottom of the pycnocline and corresponded to about 10% of the surface light level whereas in winter this layer occurred at either the top or in the middle of the pycnocline and corresponded to about 20% of the surface light level. They found a close relationship between the depth of the CML and the nutricline, particularly that of nitrate. Below the maximum, there was a general decline in the concentration of chlorophyll.

1.2 Primary production levels

The photic zone off Keahole extends to about 125 m. Primary productivity rates were somewhat higher in shallow levels but surprisingly uniform throughout the photic zone (Noda et al. 1980, Figure 12). The significant feature of the data was the wide variation among the six cruises. Covariance analysis gave a statistically significant correlation. The average depth-integrated phaeopigment values and the depth-integrated primary productivity value were significantly correlated ($r = 0.92$; d.f. = 4; $P < 0.01$) whereas the depth-integrated chlorophyll and the integrated primary productivity values showed no significant correlation. Noda et al. concluded that the input rate of regenerated nutrients has a strong positive effect on the rates of primary production off Keahole. Total primary productivity over six cruises ranged from 0.72 to 18.70 $mgC/m^2/h$ or 8.64-224.40 $mgC/m^2/day$. Annual primary production varied from 12.04 to 101.11 $gC/m^2/yr$. Wide natural variation in primary productivity rates is a typical feature of the Keahole Point marine environment.

Compared with other net primary productivity values obtained from different areas of the world's ocean, the area off Keahole is sometimes as productive as the Sargasso Sea, which has a net primary production of 70-145 $gC/m^2/yr$, but far less productive than the Gulf of Guinea (365 $gC/m^2/yr$) and Long Island Sound (190 $gC/m^2/yr$) (Dunbar 1975). The normal rate of primary production in oceanic waters has been estimated by Riley (1970) to vary from 50 to 150 $gC/m^2/yr$ (150 to 300 g dry weight/m^2/yr).

Primary productivity in the DOMES area was generally low (El-Sayed and Taguchi 1979). These results agreed quite well with those of other studies in the same or adjacent area. Primary production values at the surface in summer averaged 1.5 $mgC/m^3/day$ whereas in winter it reached 2.7 $mgC/m^3/day$. The daily primary production in the euphotic zone was 120 $mgC/m^2/day$ in summer and 144 $mgC/m^2/day$ in winter. Maximum primary production was at 50% of the surface light level in the summer but was found at or near the surface in winter. In summer and winter, nannoplankton (<20 μm) contribution to primary production averaged 77%. Nannoplankton contribution to total primary production was lower in winter (about 63%) than in summer (83.3%). Phytoplankton production below the euphotic zone, at an average depth of 104 m, contributed about 5% of the total production in the water column. Unlike the phytoplankton standing crop, primary production was not controlled by the depth of the mixed layer.

El-Sayed and Taguchi (1979) also found significant spatial and seasonal variation in the phytoplankton standing crop and primary production. They concluded that whereas the phytoplankton standing crop is likely to be controlled by the depth of the mixed layer, primary production

was independent of it. Phytoplankton and zooplankton data suggested that
the DOMES area is at a near steady state for an interval of a few days.
This indicated that the feeding of the zooplankton on phytoplankton
apparently balanced production by phytoplankton.

1.3 Compensation depth

The number of quanta required for the evolution of one molecule of
oxygen by green plants has been shown to vary from 3 to 10 quanta/O_2 (Forti
1966). The wide variation in these measurements results from not only
difficulty in the experimental methodology but also because respiration
occurs simultaneously with photosynthesis. Under conditions of light
saturation, the rate of photosynthesis is up to 20 times higher than the
rate of respiration; however, at lower light intensity deeper in the water
column, a depth is reached where light intensity is just sufficient to
bring about a balance between the oxygen produced through photosynthesis
and that consumed through respiration. The depth at which this balance
occurs is called the compensation depth.

The compensation depth in ocean ecosystem is, therefore, the division
between an upper euphotic or trophogenic zone where primary production is
possible, and a lower zone where biological activity is confined to
consumption of imported energy (Westlake 1966). During highly productive
periods, the compensation depth is approximately the same as the depth of
the mixed layer. The effective biomass of primary producers includes the
populations above and below the thermocline. If the compensation depth is
above the thermocline, phytoplankton may sometimes be near the surface and
are capable of positive net photosynthesis; however, at greater depth, they
can only respire but be still available as a food source. In such a
situation, the gross productivity per unit area will not be affected, but
net productivity will be reduced because of the respiring population below
the compensation depth. Compensation depth can vary with season,
illumination, turbidity, and other factors.

Increases in phytoplankton biomass and assimilation rate can occur
only in water layers which receive a minimum illumination of 400 lx
(Moiseev 1969). Below this level, photosynthesis and proliferation cease
and phytoplankton perish. In the summer compensation depth, has been
estimated to be less than 50-100 m in the North and South Pacific about
80-120 m in the equatorial Pacific, and about 100-140 m in the subtropical
regions.

Compensation depth can be approximated in field work as the depth at
which light is attenuated to 1% of the surface radiation and can be
estimated with a bathyphotometer or doubling the depth of the Secchi-disk
visibility (Parsons and Takahashi 1973). Below the compensation depth,
there is no net photosynthesis. The photic zone was 125 m at Keahole Point
and 145 m at Kahe Point, which is characteristic of clear-blue ocean waters
(Noda et al. 1980, 1981b).

1.4 Operational and post-operational results

Baseline data for an open ocean site are available for the operational phase of OTEC-1 and the post-operational phase. Results of these studies are summarized in the following section.

Biomass

To evaluate the effects on the environment during operational and post-operational phases of an OTEC facility, Noda et al. (1981a) carried out two special sampling cruises at the OTEC-1 site off Keahole Point. The first cruise in January 1981 (HOTEC-11) monitored the environment during the operational phase of OTEC-1 and the second cruise in April 1981 (HOTEC-12) sampled the area during the post-operational phase.

During the operational phase chlorophyll maximum values were significantly lower than those obtained during the benchmark survey in October 1978-December 1979. Furthermore, the maximum was not only deeper than observed previously but also significantly deeper at the OTEC-1 platform and downstream of the platform than at the control station. The depth-integrated chlorophyll value at the platform was 14% higher and 65% higher downstream of the platform than at the control.

Noda et al. (1981a) also found that maximum phaeopigment concentrations at subsurface levels exceeded values described earlier and were higher at the platform and downstream than at the control station. The depths of the phaeopigment maxima were significantly deeper at the platform and downstream than they were at the control station or when compared with the benchmark data. Also, significantly lower depth-integrated phaeopigment values were found at the platform and downstream than at the control.

Vertical profiles of in vivo fluorescence, measured to about 110 m, supported the vertical distribution pattern observed in the hydrocast data and showed an increase in chlorophyll at a shallower depth at the control station, which suggested that there were differences in the distribution of chlorophyll at the three stations.

Depth-integrated ATP values fell within the range of the historical data but they were significantly higher by 64% at the downstream station than at the control (Noda et al. 1981a). These results were in good agreement with the chlorophyll data from HOTEC-11.

Noda et al. (1981a) compared the results obtained from Site 1, a control station, and Site 2, which was representative of the OTEC-1 location, and found that the overall chlorophyll values showed similar ranges and patterns of distribution in the water column at Sites 1 and 2. Depth-integrated chlorophyll a values and depth-integrated phaeopigment levels were also very similar and not significantly different between sites.

The ATP concentrations ranged from 3.98 to 49.79 ng/liter overall and the highest value occurred at 70 m or just above the depth of the chlorophyll maximum at Site 1 but not at Site 2. However, because the

distribution pattern of ATP with depth at either site revealed the systematic development of a subsurface maximum, the absence of one is rather typical of the vertical pattern of ATP. Total microbial biomass and the mean depth-integrated ATP values showed similar levels at both sites.

Primary productivity levels

Of considerable interest are the primary productivity data. Photosynthetic rates were significantly higher at Site 2 near the OTEC-1 mooring buoy than at the control station (Noda et al. 1981a). Depth-integrated primary production averaged 14.53 ± 0.86 mgC/m^2/h at Site 1 whereas at Site 2, the average was 28.66 ± 3.14 mgC/m^2/h. The coefficients of variation for the two sets of data were 0.03 and 0.11, respectively, indicating good precision for the average estimates derived for both sites.

Noda et al. also compared their results from HOTEC-12 with those from the benchmark cruises. They found that data from the control station during HOTEC-12 fell within the range of primary productivity rates from the benchmark cruises but data from near OTEC-1 fell outside. Statistical tests confirmed that Site 2 had significantly higher primary productivity than was typical for the area. Phytoplankton biomass (chlorophyll a) and total microbial biomass (ATP), however, showed no statistical difference at Sites 1 and 2. Noda et al., therefore, concluded that although primary productivity was significantly different between Sites 1 and 2, and between Site 2 and the benchmark data, it appeared that the changes in the rate of photosynthetic activity, rather than differences in the standing stock, were the primary motivators for the higher productivity.

Vertical distributions of cell density at the two sites during HOTEC-12 were dissimilar, but this was attributed to the naturally large variability and the restricted number of analysis (Noda et al. 1981a). The data, however, did provide a synoptic picture of the composition of the primary trophic level. Numerically, the concentrations were higher for the large and small cells, but Noda et al. attributed the differences between cruises HOTEC-11 and HOTEC-12 to sample collection and preparation procedures and not to actual changes in size structure.

Compensation depth

During the operation phase of OTEC-1, the extinction coefficient for light was 0.0325/m, thus describing the floor of the photic zone at 128.5 m (Noda et al. 1981a). No significant difference was found in the primary productivity rates among the three stations occupied during HOTEC-11, but similarities were found between the rates calculated from HOTEC-11 and those observed during the benchmark survey.

Vertical profiles of in vivo fluorescense were similar at both sites (Noda et al. 1981a). Both traces showed a surface layer, 50-60 m thick of relatively uniform signal from the fluorometer. Subsurface maxima were between 80 and 100 m. Vertical profiles of submarine light, made to a depth of 90 m at both sites, showed that the extinction coefficient was -0.0346/m at Site 1, whereas it was -0.030/m at Site 2. The time-integrated quantum flux during the incubation periods (carbon fixation

experiments) was 12.0×10^{20} quanta/cm^2 in 8.75 h at Sites 1 whereas it was 7.80×10^{20} quanta/cm^2 in 6.5 h at Site 2. Noda et al. concluded that the average light field on the 2 days of sampling was very similar with only a 12% difference on a per-hour basis.

1.5 Plume survey

Noda et al. (1981c) carried out a plume survey using the OTEC-1 system aboard the OEC to (1) locate and map the physical extent of the thermal plume, both vertically and horizontally, (2) determine the dilution of the discharging effluent with ambient water as a function of location, (3) measure dissolved oxygen, salinity, and nutrients, and (4) measure ATP, chlorophyll a, phaeopigments, and zooplankton volumes.

The OTEC-1 system was designed with a mixed-water discharge 1.8 m in diameter directed downward just below the bottom of the hull at a depth of about 8 m. Discharge rates were about 9.8 m^3/min which resulted in an exit velocity of 3.8 m/sec.

Data on several characteristics of the plume can be found in Noda et al. (1981c). They found that there were no significant differences between the chlorophyll, phaeopigment, and phaeopigment/chlorophyll (P/C) ratios in the plume and at a control station located at a depth of 25 m. Total microbial biomass (ATP), however, was significantly lower in the plume than at the control station, and the mean was only 61% of the control mean. Analysis of differences in pigments at each depth showed no significant difference between the plume and the control station.

By chi-square analysis, Noda et al. (1981c) also demonstrated that the frequency of lower ATP and chlorophyll values in the plume at various depths did not differ significantly from what would be expected by random chance and that there was a significantly higher frequency of phaeopigment and P/C ratios in the plume than at the control station.

2. Community composition

Specific information on phytoplankton community composition is available from water samples collected during the DOMES survey. Fryxell et al. (1979) classified these waters as oligotrophic but rich in the number of species present.

Ocean species of phytoplankton tend to be widely distributed. Fryxell et al. observed that half of the diatoms and about 57% of the dinoflagellates found in the DOMES area also occurred in the Mozambique Channel as reported by Sournia (1970). Semina (1974) listed over 1,000 taxa of phytoplankton from the Pacific. Table 3, which shows the number of species found from other studies together with those by Semina (1974), illustrates the large number of taxa occurring in the Pacific. Most are involved in primary production.

The 10 most abundant taxa found in the DOMES samples by Fryxell et al. are shown in Table 4. The flagellate and monad groups are combined and

shown as a single category; this group was by far the most abundant. The Gymnodiniaceae included all the dinoflagellates with nonrigid thecae that "round up" when preserved and several species were most likely included. "Yellow cells" include resting or reproducing cells full of storage material but with little morphological details that can be used to distinguish them.

Among the coccolithophores, Gephyrocapsa huxleyi (= Coccolithus huxleyi) was the most abundant, contributing nearly 60% of the total coccolithophorid cells and was also the most abundant species in the chlorophyll a maximum layer. It was increasingly dominant among coccolithophore species at all depths from about lat. 30°N to higher latitudes; in fact, it was practically the only coccolithophore present north of lat. 40°N to subarctic waters (Okada and Honjo 1973). Gephyrocapsa huxleyi also constituted from 25 to 50% of the coccolithophores in the zone described by Okada and Honjo as the "equatorial north."

Species of phytoplankton that occurred in samples from every station included two diatoms, three taxa of dinoflagellates, two coccolithophores, and two unidentified taxa. Taxa found at or below the chlorophyll a maximum layer included 31 diatoms, 19 dinoflagellates, and 9 coccolithophores (Fryxell et al. 1979).

Most of the species that occurred below the euphotic zone were found in small numbers and Fryxell et al. regarded them as "rare species" rather than truly "shade flora." They concluded that coccolithophores are an important group in the ecosystem of tropical and subtropical waters. They occur in roughly the same numbers as diatoms and dinoflagellates but most are small.

At Keahole, a substantial proportion of the phytoplankton biomass consisted of very small-celled organisms, usually less than 5 µm (Noda et al. 1980). Because these organisms are a characteristic feature of oligotrophic waters and potentially responsive to nutrient enrichment, Noda et al. (1981a) conducted detailed analysis of these organisms during HOTEC-11. Size structure analysis showed that most of the phytoplankton biomass was in the <5 µm fraction. The fraction of chlorophyll biomass in the <5 µm fraction was significantly lower at the downstream station than at the control.

In the >5 µm fraction, the total cell volume at the control station was significantly higher than that at either the platform or downstream. Furthermore, in terms of cell density, the groups could be ranked in order of importance as: flagellates, dinoflagellates, diatoms, coccolithophores, and in terms of cell volumes, dinoflagellates, flagellates, diatoms, coccolithophores.

At the generic and specific levels, Noda et al. found that dinoflagellates were the largest and most conspicuous element of the phytoplankton community off Keahole Point. Large species such as Ceratium pentagonium, C. declinatum, C. teres, and C. schranbii, were seen in almost all samples whereas C. furen and C. fusus occurred only occasionally. The

genera of dinoflagellates observed included Oxytoxum, Gonyaulax, Peridinium, Amphidinium, Ornithecircus, Gymnodinium, Podolampas, Pyrocystus, Gyrodinium, and Dinophysis.

Noda et al. (1981a) also frequently encountered dinoflagellate cysts in the samples. Numerically, small dinoflagellates were important including Prorocentrum sp., Peridinium sp., Amphidinium sp., Gyrodinium sp., Gymnodinium sp., and Oxytoxum sp. Among the important centric diatoms in terms of cell volume were Coscinodiscus, Rhizosolanis, Licomorpha, Hemiaulus, Leptocylindrus, Planktoniella, and Acinopticus. Small pennates most predominant numerically included Navicula, Nitzchia, and Gyrosigma. Coccolithophores included Discophaera tubifer, which was found in nearly every sample, and other genera including Emiliamai, Gephyrocapsa, and numerous others. Flagellates in the samples were represented by Cryptophyceae, Chrysophyceae, Haptophyceae, and Choanoflagellata.

Johnson and Horne (1979), in their study of phytoplankton and biomass distribution at potential OTEC sites, reported that in Hawaii the net phytoplankton population was diverse including 76 identified species. In terms of numerical abundance, four species of pennate diatoms predominated including Dactyliosolen mediterraneus, Nitzschia closterium, Navicula sp., an unidentified athecate dinoflagellates.

All species and groups identified from Hawaiian waters were ranked (Table 5).

3. Seasonal variation

Differences in phytoplankton quantities are caused in part by differences in the reproductive rate of algae and in the grazing activity of zooplankton. Cushing (1981) reported that in temperate waters, the seasonal production of algae may be considered as a wave of high amplitude lasting 6-12 weeks which later subsides to much lower levels. In subtropical and tropical seas, however, the seasonal differences are much less pronounced. The exceptions are, of course, the upwelling areas where cycles analogous to those in temperate seas occur.

In the DOMES study area, chlorophyll a values averaged 0.063 mg/m^3 in summer and 0.17 mg/m^3 in winter (El-Sayed and Taguchi 1979). In the euphotic zone, the average value was only 9.8 mg/m^2 in the winter. Seasonal variations in other values were also found and these were discussed in earlier sections.

El-Sayed and Taguchi also found the CML at a depth of about 10% (summer) and 20% (winter) surface light level. Concentration in the chlorophyll maximum exceeded surface values by a factor of 3.6 ± 1.9 in summer and by 1.8 ± 0.8 in winter. At the CML, the proportion of chlorophyll a to total pigments (chlorophyll a plus phaeopigments) was lower (0.44 ± 0.06) in summer than in winter (0.56 ± 0.13).

B. Differences at Island Sites

Data collected during surveys conducted at Kahe Point are useful in examining differences in biological parameters between open ocean (Keahole and DOMES) sites and nearshore island sites. The Kahe Point surveys are particularly useful because not only has the site been selected for an OTEC pilot plant but also because much of the environmental surveys were completed before the construction of Hawaiian Electric's oil-fired generating plant at Kahe Point. Also, the location has been surveyed extensively during the O'OTEC cruises (Noda et al. 1981b; Noda and Associates 1982).

1. Kahe Point

In a study to obtain baseline data from waters off Kahe Point, Noda et al. (1981b) carried out a shipboard measurement program from May 1980 to May 1981. Bimonthly cruises were made to the following two O'OTEC benchmark sites off Kahe Point:

o Site 1, at lat. $21^\circ 19.5'N$ and long. $158^\circ 12.5'W$, approximately
   4.9 nmi west-southwest of Kahe Point (Figure 13).

o Site 2, about 4.7 nmi west-southwest of Maili Point, at
   lat. $21^\circ 23.5'N$ and long. $158^\circ 15.5'W$.

Biomass

Based on results of six cruises, Noda et al. (1981b) reported that in the Kahe environment, there is a deep CML which is characteristic of many other oceanic systems and which represents an important facet of phytoplankton ecology. In time and space, the chlorophyll maximum remained about the same in vertical position (86 m) as well as in concentration (average = 0.27 µg/liter). This layer accounted for 77% of the chlorophyll biomass in the photic zone. About 60-80% of the cells were in the <3 µm size fraction. Pigment levels were low and uniform down to 44 m, and averaged 19.90 ± 2.31 mg chlorophyll a/m^2 and 18.69 ± 5.34 mg phaeopigments/m^2 over the year. Pigments also showed considerable uniformity over time except at both stations in August 1980 and at Station 1 in October 1980.

Primary production

The average annual primary production for the Kahe area was 60.4 ± 15.6 gC/m^2/yr, a value similar to those for other subtropical gyre waters (Eppley et al. 1973; Gilmartin and Revelante 1974; Gundersen et al. 1976; Bienfang and Gundersen 1977; Sharp et al. 1980; Bienfang and Szyper 1982). The ratio of productivity to biomass, which is useful as a relative index of specific rates of photosynthesis, showed that the characteristic feature of the Kahe system is persistent nutrient limitation and that phytoplankton in the area are growing slowly. Noda et al. also observed a temporal pattern to the P/B ratios which paralleled that of photosynthesis. In the light-saturated layer, they found low P/B ratios from May to December and

generally higher ratios from January to May, which suggested a relaxation in the degree of nutrient impoverishment.

The results also indicated that photosynthesis in the light-saturated layer accounted for only 30% of the total production. Temporal variability, according to the authors, was due to changes in the activity of populations found in the light-limited layer. There was a highly significant positive correlation between fraction of production taking place below 44 m and that in the total water column (Noda et al. 1981b).

To determine which of the various processes influenced production in the light-limited layer, Noda et al. examined different variables but could not identify any which had a consistent seasonal pattern that would provide an explanation. They did, however, find that the temporal pattern of primary productivity had a general correspondence with local wind patterns, that is, during December-April when productivity was highest, the frequency of northeast, east, and southeast trades was lowest. Primary production was lowest from May to November, slightly higher from December through March, then low once again in May. The coupling between wind activity and ocean circulation, however, remains undelineated. The circulation off Kahe suggests that upwelling occurs during eddy formation, but it is insufficient in strength and duration to significantly affect the sea surface. It is reasonable to assume, however, that the lower regions of the photic zone are affected.

Compensation depth

The calculated depth of the 1% light level off Kahe Point ranged from 142 to 150 m and averaged 146 m (Noda et al. 1981b). The compensation depth at Kahe, therefore, is not dissimilar from the results obtained by Gundersen et al. (1976), who calculated the photic zone (defined according to the 1% light level) at Station B at 140 m in the Kealaikahiki Channel (between the Islands of Lanai and Kahoolawe at lat. $20^{\circ}41'N$ and long. $156^{\circ}55'W$).

Community composition

Throughout the photic zone extending down to 145 m, 65% of the microbial biomass in the Kahe environment is represented by organisms in the ≤ 3 μm size fraction (Noda et al. 1981b). Takahashi and Bienfang[3] reported that the vertical distribution of picoplankton is not influenced by sinking, thus reinforcing its dominance in a nutrient-limited environment. In addition, the picoplankton's potential for ammonium uptake at low levels favors its success in a substrate (light or nutrient) limited system. Takahashi and Bienfang found that the <3 μm fraction assimilates ammonium at rates 75% faster than those for the large 3-20 μm fraction. Thus, in the CML the picoplankton can take advantage of higher nutrient supply without being subjected to the hazards of sinking and therefore, being transported to light-deficient depths where photosynthesis is absent.

Noda et al. (1981b) suggested that the dominance of picoplankton off Kahe may be related to the prevailing nutrient field. Modest climatic fluctuations in the Kahe area produces thermal stratification which

persists thus restricting vertical input from deep nutrient-rich water. This produces an environment driven by regenerated nutrients and results in a condition characterized by numerous, small nutrient inputs, low ambient concentrations, and an importance of reduced forms of nitrogen.

Seasonal variations

Noda et al. (1981b) found considerable uniformity in pigment levels over time at Kahe Point, but there were exceptions particularly when large divergences occurred at both sites during August 1980 and at Site 1 in October 1980. The ATP values were highest in August-January but displayed a relatively even pattern the remainder of the year. Photosynthetic rates showed a consistent upward trend from low values in May-November 1980, increasing levels through March 1981, and slightly lower values to May 1981. Temporal variations were usually significant. Noda et al. concluded that although photosynthetic rates showed a significant increase during the second half of the survey period, the biomass parameters showed little regularity and unlike the photosynthetic rate no significant changes occurred. They reported that it was not clear whether any ecological significance can be attached to temporal variability of the biomass parameter.

Because two scales of spatial variability occurred during the Kahe survey, each was addressed by Noda et al. (1981b). Cast-to-cast differences were examined for small-scale spatial variability arising from the ship's drift during sampling; the average distance between hydrocasts was 0.9 km. Station-to-station differences were termed large-scale spatial variability and represented an average of 9 km on the horizontal scale.

The results clearly indicated that large-scale spatial differences in biomass parameters were not great. Noda et al. noted that although comparison of time-averaged values of the various parameters may indicate station-to-station differences since values at one station may exceed those at the other rather consistently, the differences between the means were not significant.

In nearly all the comparisons for photosynthesis, however, Noda et al. found that the Station 2 mean was higher than that for Station 11 and the absolute difference averaged 5.26 $mgC/m^2/h$ over the year of the study. This translated into 47% higher photosynthetic rate at Station 2. Thus, although absolute values of the station-to-station differences were not large in comparison with temporal variations observed earlier, the ability to measure differences between station may prove useful in future monitoring programs which assess the areal extent of impact to biological productivity resulting from the operation of an OTEC plant at Kahe. Noda et al. concluded that because large-scale spatial differences were not pronounced, small-scale differences were even less important.

Criteria standards for the Kahe environment

From the baseline data collected for the Kahe environment, Noda et al. (1981b) calculated the natural range of phytoplankton density, expressed as the 95% confidence limits for the depth-integrated data (Table 6). Also,

based on the given analytical capability and observed temporal and spatial variabilities at Kahe, they used the analysis of variance data to determine criteria for detecting significant environmental changes. They reasoned that the detection of significant differences between two measurements depends on precise measurements of the level below it; for example, analytical precision depends on precise measurements to detect any subsample variation. Table 7 gives the criteria for detecting significant ($P = 0.05$) differences for each parameter and for each level under examination.

2. Differences between the Keahole and Kahe environments

Noda et al. (1981b) compared the two oligotrophic Hawaiian ecosystems surveyed during the HOTEC and O'OTEC programs. Table 8 gives the values of the phytoplankton parameters off Keahole and Kahe Points; Table 9 summarizes the conclusions drawn by Noda et al. with respect to the various parameters compared.

Noda et al. suggested that differences in the nature and magnitude of temporal variations between the Kahe and Keahole environments may be related to the physical environments. The Keahole system, which is

adjacent to the deep Alenuihaha Channel over which wind strength increases due to the Venturi effects caused by high mountains, is exposed to large, rapid fluctuations in wind force, wave height, and water movement. Variability in these processes is thought to produce the complex biological systems that were observed in the environment. In contrast, Kahe is exposed to less intense winds that blow over the Kauai Channel. Because wind intensity is associated with divergence and upwelling, it is reasonable to expect that these processes are less intense off Kahe than off Keahole. The isolation of the Kahe system from severe weather and intense wave action results in less variability of the physical components and more gradual and systematic temporal cycles in the biological components.

3. Response of phytoplankton to nutrient enrichment

In subtropical regions where thermal stratification results from the absence of pronounced seasonal climatic variation, the nutrient-poor surface waters are isolated from the nutrient-rich deep waters.

Two processes govern the productivity of the ecosystem in the mixed layer--the availability of inorganic nutrients such as nitrates and phosphates and the availability of light. With increasing depth, light intensity decreases logarithmically to about 1% of the surface intensity. The relative availability of light and nutrients creates a transition from the nutrient-poor surface layer to the light-limited deep layer. Below the transition zone, light energy is too low for phytoplankton to occur (Yentsch 1966).

The amount of light in the euphotic zone is dictated by geography, season, time of day, the surface, and the transparency of sea water (Yentsch 1966). Light penetration is reduced if the ocean surface is

disturbed by wind action. Likewise, water transparency is reduced by the introduction of inorganic and organic suspended particles. Water itself can modify the wave lengths which penetrate it.

Because OTEC introduces large quantities of nutrient-rich deep water into a nutrient-poor surface layer at a rapid rate, unlike natural oceanic and coastal upwellings which are diffuse and slower, it is expected that biostimulation of phytoplankton will occur in the affected areas. For example, water drawn from 910 m will be high in nitrates and phosphates but low in oxygen and pH indicating elevated inorganic carbon concentrations ([Hawaii.] Department of Planning and Economic Development (DPED) 1980). When this deep water is finally discharged as effluent into the normally nutrient poor surface water, biostimulation should increase the rate of primary production several fold, provided that there is sufficient time for substantial photosynthesis to occur before the effluent sinks to a depth where the surrounding water is of the same density.

At sites approximately 12 nmi northwest of Keahole Point and also 6 nmi west of Kahe Point, Bienfang and Szyper (1982) performed nutrient enrichment experiments on water collected from nine target depths--2, 10, 30, 50, 70, 90, 110, 130, and 150 m. Their analysis demonstrated that deep-water enrichment produced immediate biostimulation of phytoplankton activity, and the degree of response was dependent on light availability with depth. The data also indicated that in the photic zone, the additive effect as a result of deep-water addition ranged from 1.23 to 5.47 $mgC/m^2/h$ representing increases of 9.3 to 149.0% over natural levels.

Bienfang and Szyper also found that short-term increases in carbon fixation caused by nutrient enrichment within the light-saturated layer represented an alleviation of the strongly nutrient-limited conditions. They concluded that all the additional nutrients supplied were probably not exhausted during the 11 hours of incubation and attributed this phenomenon, together with the inherent response capabilities of the phytoplankton population, as having influenced the degree of biostimulation.

Biostimulation, which was depth dependent and related to availability of light, was not present in the deepest samples collected at 100 m or deeper. Bienfang and Szyper attributed this lack of biostimulation to ambient nutrient concentrations in the water column which increased below 90 m, thus making excess nutrients superfluous. They also reported that there was a range of depths in which ambient nutrients were low and yet addition of deep-water nutrients did not induce biostimulation. These depths are below those of K_L light levels, but well above the depths where ambient nutrients began to increase (Table 10).

Low ambient nutrient level in the transition zone, where the upper limits ranged between 24 and 61 m and lower limit was around 90 m, indicates phytoplankton uptake paralleling the rates of nutrient supply (Bienfang and Szyper 1982). This suggested that, together with the low P/B ratios, photosynthesis in this layer was limited, at least partly, by nutrient availability. Furthermore, lack of response to deepwater nutrient addition suggested that light availability also influenced photosynthesis in this zone.

Evidently, information on the lower region of the transition zone is critical to the understanding of oceanic phytoplankton dynamics. Despite light limitations at this depth, the plant cells apparently utilize the available light rather efficiently thus attaining more than 60% of the theoretical maximum quantum yield in carbon fixation in the CML. The maximum absolute carbon fixation rate was at a depth of 70 m in oceanic waters off Oahu (Bienfang and Gundersen 1977). Bienfang and Szyper (1982) found no indication of a photosynthetic maxima at either the Keahole or Kahe Point sampling sites; however, they did find that the depth of the CML off Keahole Point was 85 ± 9 m which corresponded roughly to the bottom of the transition zone. Because ambient nutrient concentrations were consistently low where these chlorophyll maxima occurred, they concluded that this was an indication of active metabolism by the phytoplankton.

Finally, Bienfang and Szyper (1982) reported that the mixture of surface and deep water discharged by OTEC facilities will spread from the site at depths having similar densities and that these depths will be in he transition zone. Little immediate biostimulation will result in areas where the discharge mixes with oceanic waters and becomes diluted.

III. ZOOPLANKTON

Animals comprising the zooplankton include many of the passively floating or weakly swimming heterotrophic organisms in the water column such as protozoa, especially tintinnids, radiolarians, and foraminifera; large numbers of small crustaceans, like copepods, ostracods, euphausiids, and amphipods; jellyfishes, siphonophores, and worms; molluscs, such as pteropods and heteropods; and eggs and larvae of numerous benthic and nektonic animals (Sverdrup et al. 1946). For convenience, zooplankton can be further divided into microzooplankton, macrozooplankton, and ichthyoplankton. Microzooplankton, which includes organisms such as naupliar and copepodid stages of copepods, ciliate and sarcodine protozoans, and larvaceans, pass through the 202-μm mesh fraction of filtration netting. Macrozooplankton, which is dominated by copepods and chaetognaths but superimposed in surface waters by eggs and larvae of many nearshore invertebrates and fish, are retained in a 202-μm mesh net (Sullivan et al. 1981). The following section will discuss only the microzooplankton and macrozooplankton. The ichthyoplankton will be addressed in a later section of this report.

A. Open-Ocean Sites

Results of zooplankton studies conducted during HOTEC-1 through HOTEC-6 (Noda et al. 1980), HOTEC-11 and HOTEC-12 (Noda et al. 1981a), a plume survey (Noda et al. 1981c), and the DOMES survey (Hirota 1977) have been reviewed and are discussed in the section that follows.

1. Biomass and composition—mixed layer

During HOTEC cruises 1 through 4, because of a limited sampling program, Noda et al. (1980) made only general observations on the zooplankton population off Keahole. Briefly, they found that calanoid copepods, by far the most abundant taxonomic group numerically, included

many species that appeared to make extensive diel vertical migrations. Noda et al. also noted significant seasonal changes in the biomass which were not correlated with any of the parameters examined.

On HOTEC-11 and HOTEC-12, there were no significant differences in the dry weight of zooplankton for each depth between cruises or among stations (Noda et al. 1981a). Like the O'OTEC biomass data, dry weight decreased from the surface to the deep strata and was higher at night.

There were also no significant differences at any depth between HOTEC and O'OTEC dry weight biomass data. HOTEC-11 and HOTEC-12 data were also compared with those from HOTEC-1 through HOTEC-6. Measurements of biomass were not significantly different.

During the plume survey, Noda et al. (1981c) collected four samples each from within and out of the plume (control). Copepods collected in a 500-µm mesh net and stained with Neutral Red were considered alive if the stain was visible in any part of their bodies.

Using a minimum sample size of 200 copepods, and all specimens in samples of Euchaeta marina, Neocalanus robustior, and Corycaeus sp., Noda et al. found that mortalities in the control ranged from 1.1 to 7.5% whereas those in the plume samples ranged between 0.5 and 21.6%. Statistical tests indicated that there was a significantly higher mortality in the plume but no differences among the species.

Estimates of the mortalities in each plume sample due solely to OTEC-1 operation were obtained by subtracting the mean mortality in the control samples from that in the plume. Multiplying the net mortality percentages by the dilution of the plume assessed from fluorometer traces, Noda et al. (1981c) estimated that the mean mortality rate of animals in the warm-water intake of the plant was 100% of entrained animals.

In the analysis of zooplankton abundance and biomass, Noda et al. (1981c) again used four samples each from within and outside the plume. The results showed that the in-plume samples had significantly lower biomass, both in dry weight and ash-free dry weight, but significantly higher percentage of ash than the controls (Table 11).

Noda et al. could not determine whether the differences in biomass were caused by the plume discharge, by the presence of the OTEC-1 platform itself, or by patchiness. They suggested that the differences in percentage of ash may have been the result of either the discharge operation or the presence of the platform. Quantitatively, the plume samples differed from the control in that the former contained a great deal of detritus and microorganisms bound in a matrix of mucous, the source of which was unknown, as well as numerous hydroids and bryozoans which originated from the hull of the vessel.

Zooplankton counts from in-plume and out-plume samples showed little variation except among the most common copepods, the calanoids, which were significantly more abundant outside the plume than within it.

Noda et al. noted that biomass in the 0-200 m stratum during ECTEC-11 and HOTEC-12 was 4.90 mg/m^3 whereas that for HOTEC cruises 1-6 was of 3.32 mg/m^3. Although the mean for HOTEC-11 and HOTEC-12 was higher, the difference was not significant. They speculated that the slightly higher value for HOTEC-11 and HOTEC-12 may have been the result of differences in handling of the samples. Calanoid copepods predominated in the samples and macroplankton counts showed no clear trend. Thus, no effect from operation of OTEC-1 could be detected in the zooplankton population.

2. Changes with depth

At Keahole, dry weight of zooplankton decreased from the surface to the deep strata and were higher by night than by day in shallow tows (Noda et al. 1981a). The trends in catches by depth are shown in Figure 14.

Analysis of vertical distribution of macrozooplankton in the water column from the DOMES survey showed the highest concentration in the upper 150 m, both day and night, and moderately high concentration between 200 and 900 m (Hirota 1977). Concentrations were usually low near 200 m at Site C and at all sites below 800-900 m.

Table 12 shows the data on standing stocks of macrozooplankton integrated over the upper 1,000 m. Standing stocks in the upper 200 m varied from about 50 to 90% of that for the upper 1,000 m (Hirota 1977).

Concerning the microzooplankton in the DOMES area, Hirota (1977) found the following major features of vertical distribution:

o Total nauplii, tintinnids, and _Microsetella_ tend to be most numerous at depths less than 40-60 m.

o _Oncaea_ abundance reached a maximum at depths usually greater than 100 m.

o Radiolaria and Foraminifera showed relatively small depth variation compared with nauplii, tintinnids, _Microsetella_, and _Oncaea_, and were common at all depths sampled.

o There were at least twofold diel variation in abundance above 75 m for nauplii, tintinnids, and _Microsetella_, and deeper than 75 m for _Oncaea_.

o _Microsetella_ was either absent or low in abundance most consistently at depths below 100 m.

o The vertical distributions of the five major microplankton taxa were not correlated with hydrographic or algal abundance; however, nauplii, tintinnids, and _Microsetella_ were most likely to be associated with the chlorophyll maximum and discontinuity layers.

Hirota compared numerical abundances of each of the five microplankton taxa with those obtained from around Hawaii (Gundersen et al. 1976) and in the EASTROPAC area (Beers and Stewart 1971) and concluded that the DOMES

area concentrations were lower than those in EASTROPAC by about twofold or more but overlapped in range of values reported from off Hawaii.

3. Seasonal variation

The results of the Keahole sampling showed that zooplankton in the offshore environment exhibited significant seasonal changes in biomass levels (Noda et al. 1980).

Hirota (1977), in reporting on the neuston, macroplankton, and microplankton abundances from the DOMES area, found differences between years (seasons) at all the sites sampled.

Studies on Hawaiian zooplankton collected in 1955-56, showed monthly variations in zooplankton volumes and peak volumes in winter, around January, a spring peak in April, and a fall peak in September (Nakamura 1967). These results contrast with those of King and Hida (1957) who found increased volumes in March-July and lower but variable volumes thereafter. Nakamura concluded that although seasonal volumes appeared to be different, their significance was clouded by some evidence of year-to-year variations. Primary productivity and zooplankton biomass in an oligotrophic gyre are not seasonal but rather related to changes over some different, perhaps longer time scale (McGowan and Hayward 1978).

4. Vertical migration

Diel vertical migrations of some species of zooplankton and micronekton have been studied extensively and are well known in warm tropical waters (Blackburn 1981). In areas of deep light penetration, these animals would be expected to have a relatively large vertical range. For example, in the Pacific, the medium daytime depth of the sound scattering layer is 335 m. Vinogradov (1968) reported that in the subpolar region, the macroplankton occupies much of the water column but diurnal migrations are weak. In the tropics, however, the macroplankton concentrates in narrow layers and undergo extensive diurnal vertical migration. One consequence of vertical movement would be the transfer of organic material to animals living at progressively greater depths. Longhurst (1976) has stated that no evidence exists of migration below 1,700 m.

Data from the HOTEC 1-6 cruises indicated that many species of zooplankton off Keahole appeared to make extensive diel vertical migrations. Nakamura (1967) concluded from his studies of zooplankton volumes in waters around Oahu, Hawaii, that polychaetes, ostracods, calanoid copepods, euphausiids, amphipods, pteropods, and fish larvae all exhibited pronounced diel variations in abundance. Among the calanoid Copepoda, genera such as _Pleuromamma_, _Neocalanus_, _Candacia_, _Undinula_, and _Euchaeta_ exhibited the most marked diel variation in abundance. _Haloptilus_ was absent from the upper layer of water.

E. Differences at Island Sites

1. Biomass and composition--mixed layer

There was an approximate tenfold difference between biomass collected
in shallow plankton tows and those from the 600-1,000 m depth range off
Kahe (Noda et al. 1981b). In the shallow tows, night-time biomass was
twice as great as that found during the day. Noda et al. also found
considerable variability in zooplankton biomass among the cruises; however,
they concluded that this variability was not related to seasonal changes.

Tables 13 to 18 show the zooplankton biomass data summarized for the
six O'OTEC cruises. The ash-free zooplankton biomass ranged from a low of
0.14 mg/m^3 to a high of 25.00 mg/m^3, both from cruise 4 in January 1981.
Variability in zooplankton biomass was attributed to several sources:
subsampling error, variability between replicate tows; differences between
stations and between day and night tows; and differences among cruises and
among depths.

2. Changes with depth

Off Kahe between the surface and 25 m, there was some evidence of
zooplankton patchiness in the portion of the population that made diel
migrations. Similar evidence of day and night differences and patchiness
was found in the remaining depth ranges above 1,000 m. Also, repeated
cruises offered better discrimination of changes than replicate stations or
samples (Noda et al. 1981b).

Noda et al. reported that it was not clear which taxa of the
zooplankton community will be most affected by OTEC deployment; it was
necessary, therefore, to undertake a broadbased investigation of all the
taxa found and their abundance. Furthermore, because of the large number
of species involved, they concluded that there is a need for a trade off
between the number of samples to be processed in a given time and the
number of taxa to be identified to genus and species.

For the O'OTEC investigation, Noda et al. identified all animals to
class except that the more abundant copepods were identified to genus when
possible and occasionally to species. In general, most taxa occurred
infrequently in all samples. Most were found more frequently in shallow
than deep water and many of the taxa common in shallow water were absent or
rare in deep water.

In all samples, copepods made up 73-85% of the total and among the
copepods, from 59 to 66% were calanoids except in the neuston samples where
calanoids accounted for 38% in day samples and 78% in night collections.
Noda et al. suggested that this exception was the result of apparent
reverse diel migration of cyclopoids of the Family Corycaeidae in and out
of the surface layer.

In summary, Noda et al. found that the most abundant group overall was
the calanoid copepods and among these, the small herbivorous calanoids of
the Families Paracalanidae and Pseudocalanidae were the predominant groups

in the shallow strata. In the deep strata, the calanoids included large,
mainly carnivorous animals.

Among the cyclopoids which were only second to calanoids in abundance,
three groups predominated—Corycaeidae, which were most abundant in surface
samples and Oithona and Oncaea which were dominant in the deep samples.
All three were abundant in the 0-25 m samples.

The patterns of absolute abundance that emerged from the study were as
follows:

o Medusae, gastropod larvae, fish eggs, Foraminifera, and Corycaeidae
were most abundant at the surface, decreased in abundance with
depth, and was more abundant at night in all layers than during the
day.

o The abundance of radiolaria, pelecypod larvae, amphipods,
chaetognaths, larvacea, salps, and copepods, such as Arocalanus
spp., Paracalanus spp., Clausocalanus spp., Euchaeta spp.,
Haloptilus spp., Candacia spp., Arcatia negligens, and Oithona
spp., was at a maximum below the surface. The abundance of neuston
and shallow water forms was greater at night.

o Ostracods, euphausiids, and copepods such as Oncaea spp.,
Pleuromamma sp., and Lucicutia spp. were most abundant
well below the surface by day. At night these species were much
more abundant than they were above 25 m during the day.

3. Seasonal variation

Off Kahe, the temporal variability of zooplankton abundance may not be
seasonal (Noda et al. 1981b). Primary productivity and zooplankton biomass
in an oligotrophic gyre are not seasonal but rather change over some
different, perhaps longer time scale (McGowan and Hayward 1978). Noda et
al. suggested that this lack of seasonality is sufficient reason for long
pre- and post-deployment sampling periods to detect long-term variability.

4. Vertical migrations

Off Kahe, organisms such as ostracods, euphausiids, and copepods like
Oncaea spp., Pleuromamma sp., and Lucicutia spp. migrated vertically, and
were found between 25 and 200 m during the day (Noda et al. 1981b).
Medusae, gastropod larvae, fish eggs, Foraminifera, and Corycaeidae were
non-migrating epipelagic animals, and radiolaria, pelecypod larvae,
amphipods, chaetognaths, larvacea, salps, and numerous copepods such as
Acrocalanus spp., Paracalanus spp., Clausocalanus spp., Euchaeta spp.,
Haloptilus spp., Candacia spp., Arcatia negligens, and Oithona spp.
appeared to have a vertical migration pattern. However, their increased
night-time abundance may be indicative of net avoidance in day-time
sampling. Their abundance in deep, daytime samples was not notably greater
than their night-time abundance which suggests that no upward migration was
occurring; however, because of the wide depth ranges used for the study,
more detailed observations are needed.

IV.   FISHES

Fishes and other nekton are expected to be attracted to an offshore OTEC structure, thus increasing their concentrations. Nektonic organisms can maintain their location and direction by swimming; however, the intake velocities of an OTEC facility may exceed swimming capabilities, particularly among small species or juveniles. As a first step toward determining OTEC entrainment and impingement impacts on nekton, the species composition and population size of fishes need to be estimated in the vicinity and downstream of the OTEC site ([Hawaii.] DPED 1980).

In waters 6-25 nmi off Kahe Point, micronekton organisms in a 1,200-m water column showed a mean standing stock of 900 organisms and a wet weight of 0.5 kg/100 m^2 of ocean surface (Maynard et al. 1975). Over half of the number of individuals and their biomasses were composed mostly of small fishes. At night, there were substantial increases in abundance of nekton in shallow water as a result of vertical migration. For micronekton determined to be inhabitants of water deeper than 400 m during the day, Maynard et al. found that about 45% migrated upward at night. During daylight hours, about 90% of the mean total micronekton standing stock were in waters deeper than 400 m ([Hawaii.] DPED 1980).

A.   Species of Commercial and Recreational Importance

The commercial fisheries in Hawaiian waters have been described by Manar (1969) and Uchida (1978). The shelf zone, on which most of the world's most productive fisheries are conducted, is narrow and poorly developed in Hawaii. Furthermore, only about 60 of the more than 682 species of fishes, mostly found on the reefs and inshore area, are commercially exploited. The major Hawaiian commercial fisheries are in the open ocean beyond 200 m in depth, where pole-and-line sampans catch skipjack tuna, Katsuwonus pelamis, and longline, handline (ika-shibi), and charter boats harvest deep- and surface-swimming yellowfin tuna, Thunnus albacares, bigeye tuna, T. obesus, albacore, T. alalunga, striped marlin, Tetrapturus audax, blue marlin, Makaira nigricans, black marlin, M. indica, swordfish, Xiphias gladius, shortbill spearfish, Tetrapturus angustirostris, sailfish, Istiphorus platypterus, wahoo, Acanthocybium solandri, and mahimahi, Coryphaena hippurus.

The nearshore fisheries, consisting of a variety of commercial handline, net, trap, and recreational boats, are mainly on a wide array of demersal and benthopelagic species which include pink snapper, Pristipomoides filamentosus, and P. sieboldii, gray snapper, Aprion virescens, red snappers, Etelis carbunculus, and E. coruscans, jacks, Carangidae, goatfish, Mulloidichthys spp. and Parupeneus spp., and sea bass, Epinephelus quernus. Bigeye scad, Selar crumenophthalmus, and mackerel scad, Decapterus macarellus are also major species in this group and their combined landings are second only to total landings of tuna and billfish.

There are a number of commercially valuable fish species in the Kahe area. The abundance of larval and juvenile tunas were studied by Higgins (1970) at a site about 7 km seaward of Kahe and very close to the proposed

offshore OTEC site. Midwater trawl catches of juvenile tunas were much
lower in this area than at another site 56 km offshore. Also, almost all
bigeye and yellowfin tunas were in the upper layers and small juvenile
skipjack tuna were most abundant in the shallow water whereas large ones
tended to be more abundant in deep water.

Data from Higgins (1970) and Miller (1979) suggest that an OTEC plant
3 nmi offshore from Kahe Point may be ideally situated with respect to
avoiding tuna larvae inshore and tuna juveniles offshore ([Hawaii.] DPED
1980).

A list of fishes of commercial and recreational value inhabiting the
offshore waters of Keahole Point has been compiled by Jones and Ryan
(1981). Table 19, which has been compiled from catch reports of the Hawaii
Division of Aquatic Resources (HDAR), lists the species caught off Keahole
and Kahe Points in 1976-80.

In Hawaii, catches are reported according to numbered fishery
statistical areas (Figure 15). The inshore area extends just beyond the
reefs, roughly 2 nmi from the coastline. The offshore area extends from
the outer boundaries of the inshore area to 20 nmi from the coastline.

Jones and Ryan (1981) also listed the following species of fishes that
were attracted to the platform and pipe during the operation of Mini-CTEC:

Spotted triggerfish	Canthidermis maculatus
Opelu	Decapterus pinnulatus
Rainbow runner	Elagatus bipinnulata
Mahimahi	Coryphaena hippurus
Pilotfish	Naucrates ductor
Whitetip shark	Pterolamiops longimanus
Kahala	Seriola dumerili
Bigeye scad	Selar crumenophthalmus
Filefish	Alutera scripta
Rudderfish	Kyphosus cinerescens
Yellow tang	Zebrasoma flavescens
Blenny	Istiblennius spp.
Damselfish	Chromis hanui
Whale shark	Rhincodon typus
Skipjack tuna	Katsuwonus pelamis
Yellowfin tuna	Thunnus albacares
Wahoo	Acanthocybium solandri

In a report describing the effects of impingement of marine organisms
at Kahe Point as a result of the operation of the existing fossil-fueled
electric generating plant, Coles et al. (1982) observed that several
commercially important invertebrates and vertebrates were affected. Among
the invertebrates were Abralia trigonura, Antarctic slipper lobster,
Paribaccus antarcticus, shrimp, Penaeus marginatus, octopus, Octopus
cyanea, kona crab, Ranina ranina, and scaly slipper lobster, Scyllarides
squammosus. None, however, were caught in sufficient numbers to merit
concern. The stomatopod, Squilla oratoria, suffered the highest loss, but
this species is not considered of great commercial value.

Among several commercially important species, only the kala, _Naso unicornis_, was affected in sufficient numbers to warrant attention. Based on extrapolation over 1 year, Coles et al. estimated that about 1,600 kala would be affected, mostly juveniles, and the projected loss would amount to 9.6 kg/yr. The amount, according to them, is well below the 7,700 kg caught in 1978 in the State of Hawaii.

B. Yield and Value

The yield and value of commercial fishing off Keahole and Kahe Points are summarized in Table 19. The data for Keahole Points are from statistical areas 121 and 122 of the Hawaii Fisheries Chart No. 2 (Figure 13). It was necessary to compile the data from these two areas because Keahole Point falls near the division of areas 121 and 122. Data for Kahe Point are from area 422.

Catch, by species, was summarized for 1976-80 and a mean annual catch determined. The values given in HDAR's catch reports are only for weight sold; therefore, the value may be underestimated if the entire catch was not sold. To derive the estimated value of the entire catch, the average price per unit weight sold was calculated from the weight sold and value information and multiplied by the actual weight caught.

The fishing grounds off Keahole and Kahe Points are high-producing regions in the Hawaiian fisheries not only for inshore reef and bottom fishes but also for pelagic species such as skipjack, yellowfin, and bigeye tunas, blue marlin, striped marlin, mahimahi, and wahoo (Table 19). Kailua-Kona, which is located along the leeward coast of the Island of Hawaii roughly 7 nmi south of Keahole Point, is recognized as one of the centers for big-game fishing in the world, and contests such as the International Billfish Tournament are held there annually. The waters off Kailua-Kona are also important for the night handline fishery (ika-shibi) for yellowfin and bigeye tunas. Kahe Point, which is located along the Waianae coast of the Island of Oahu, is a high-producing region for skipjack tuna (Uchida 1970).

Among bottom, benthopelagic, and reef fishes, important catches made off Keahole Point include amberjack, _Seriola dumerili_; snappers, _Pristipomoides filamentosus_, _Aprion virescens_, _Etelis carbunculus_, _E. coruscans_, _Lutjanus kasmira_, and _Apareus rutilans_; jacks, Carangidae; goatfish, _Mulloidichthys auriflamma_; bigeye scad, _Selar crumenophthalmus_, mackerel scad, _Decapterus macarellus_; red bigeye, Priacanthidae; and squirrelfish, _Myripristis_ spp. Off Kahe, the more important species include jacks, bigeye scad and mackerel scad, surgeonfishes, _Naso unicornis_ and _Acanthurus dussumieri_, goatfish, _Mulloidichthys samoensis_ and _M. auriflamma_, and bonefish, _Albula vulpes_. (Seaweeds, Rhodophyta and Chlorophyta, are also harvested in this area.)

C. Food Chain Effects and Other Considerations

Observations made off Campbell Industrial Park near Kahe Point revealed some interesting facts about the bottom types and inhabitants. Based on dives from 24 to 192 m in the submersible _Asherah_, Strasburg et

al. (1968) reported that the inshore area between 24 and 107 m was a sloping sandy plain interrupted by rocky ledges 3 to 18 m high. The sandy stretches were featureless and devoid of visible fauna, but in those isolated spots where coral growth or an accumulation of rocky rubble were seen, there were invariably some aggregations of fish, usually butterflyfish, Chaetodontidae, damselfish, Pomacentridae, triggerfish, Balistidae, and surgeonfish, Acanthuridae. Over the sandy bottom, they observed goatfish, Mullidae, flounders, Bothidae, bonefish, and wrasses, Labridae, whereas in midwater they saw large schools of mackerel scad, bigeye scad, jacks, and unicornfish, Naso hexacanthus. Usually, the fishes were concentrated above and in front of ledges.

Strasburg et al. also observed invertebrates in the nearshore depths. Among them were starfishes, Culcita and Linckia; Chondreocidaris, sea urchins, hydrozoans or anthozoans resembling Pennaria but including larger and heavier individuals; and extremely large spiny lobsters, Panulirus spp. that were possibly up to 60 cm long in total length and estimated to weigh 3.2 kg. One unusual aspect of the observation of spiny lobster was that they were on the open bottom unlike reef inhabiting lobsters which are found in deep, dark caves, or beneath protruding ledges. Also observed on the sandy plains were sponges, protruding tubes of annelid worms, and small brittlestars. Between 60 and 107 m, as much as two-thirds of the sea floor was covered by dense beds of a pen shell, Atrina. A bed of spatangid heart urchins consisting of thousands of individuals spaced roughly 30 cm apart were visible at 107 m. The stony coral, Porites, was observed as deep as 107 m, although their occurrence were rather uncommon.

Between 107 and 116 m, the sloping plain gave way to a steep cliff, plunging at an angle of 60°-80° from the horizontal. The cliff of smooth limestone, devoid of any macroscopic demersal fauna, had a textured quality at various places and these held silty deposits as well as gobies, longer-legged shrimp, and lobsterlike crustaceans. Ledges, caverns, and other irregularities on the cliff face sheltered crowds of squirrelfish, moray eels, butterflyfish, and other fishes. Coils of an antipatharian coelenterate, probably Cirripathes, were also common on the cliff as well as various starfish, sponges, and sea urchins down to 192 m. Beds of red coral, Stylaster and Corallium, were seen between 137 and 183 m. In addition, the cliff was "patrolled" by snappers, amberjack, wahoo, and various species of jacks, either singly or in two's and three's.

V.   ICHTHYOPLANKTON

A report which summarized ichthyoplankton population studies conducted in the vicinity of Kahe Point during the mid and late 1970's indicated that some data were nearly site specific for the OTEC site ([Hawaii.] DPED 1980). Leis (1978), who reported on 15 species of larval fish collected about 1.9 nmi from the shoreline, found median concentrations of 0-112 larvae/1,000 m^3 per species with upper ranges of 7-182 larvae/1,000 m^3 per species. He added that 100 fish larvae/1,000 m^3 would be a reasonable estimate of the mean fish larvae population at the OTEC site.

The [Hawaii.] DPED (1980) report also provided an estimate of the potential impact of an OTEC plant on the larval fish population. Assuming

that an OTEC plant would entrain about 13.8 million m^3 of surface water per day, DPED estimated that about 1.38 million fish would be impacted per day, based on the population estimate provided by Leis (1978). There is, however, a need to expand the data base on such studies so that a critical evaluation could be made on potential impact. This is particularly true of the potential impact on larval tuna populations because of the importance of adult tunas in the Hawaiian fishery. The larval tuna population in waters 0.6 nmi seaward of Kahe Point can be as high as 441/1,000 m^3 or roughly 10-100 times greater than populations found in oceanic waters of the central Pacific (Miller 1979). Miller postulated that there is a relatively deep source of these larvae, which may migrate inshore in response to upwelling of deep cold water and a shoaling of the thermocline shoreward. The [Hawaii.] DPED report concluded that tuna and other larval fish populations, therefore, may be impacted by OTEC-related alterations of the temperature structure of receiving water in the area as well as by primary entrainment.

A. Spawning Seasons and Locations

The determination of spawning season in fishes is usually based on observations on the condition of gonads, particularly ovaries. Spawning locality, however, is not readily determined unless one observes directly, the emission of ova and milt from mating pairs or observes ova attached to bottom plants, reef, or other substrate.

Other methods are also frequently used to determine spawning season and locality. The presence of larvae is good evidence that spawning occurred recently. And because larval stages of fishes are usually feeble swimmers, one can reasonably assume that the larvae have not strayed or been swept by currents very far from the actual spawning site. Some exceptions are phyllosoma stages of spiny lobsters or leptocephalus stages of anguillids that have a relatively long larval stage and which are carried for great distances by the ocean currents.

The nearshore waters of Kahe Point serve as spawning grounds for a variety of species (Miller et al. 1979). Analysis of the seasonal larval distribution indicated that they were more numerous during summer than winter.

There is also some indication that the deep waters off Kahe Point are important nursery grounds for some species of fish. Juvenile squirrelfish, Holocentrus lacteoguttatus, have been seen in large concentrations at depths between 101 and 183 m (Strasburg et al. 1968).

B. Egg and Larval Abundance and Surface Distribution

Miller et al. (1979) present data on common nearshore marine fish larvae found at Kahe Point. Their data indicate that the inshore and offshore abundance of larvae in winter at Kahe Point was below the mean level (109) for all Oahu sampling sites. In summer, the number of larvae inshore exceeded the summer mean (135) by a considerable margin; however, the offshore total was slightly below the mean.

An ichthyoplankton survey of the nearshore waters of Kauai, Oahu, and
Maui in 1972-73 disclosed abundances of tuna larvae as high as 441/1,000 m^3
(Miller 1979), an estimate 10-100 times higher than those typical of the
central Pacific. Detailed sampling at Kahe Point showed a mean of 7.7 tuna
larvae for day samples whereas the night mean was much higher (23.6).
Miller also found that day and night subsurface samples yielded higher
abundance of tuna larvae than surface samples by a factor of 4.3 and 9.7
times, respectively. The abundance of larvae increased with decreasing
distances from shore. Catches off the leeward coast were also higher than
those off the windward coast.

The longshore current near Kahe Point flows at a rate of 25-50 cm/sec
(Laevastu et al. 1964). Because the current appears to be too strong for
feebly swimming tuna larvae of 4 mm to oppose, Miller hypothesized that the
high nearshore surface densities of tuna larvae probably originated from a
deep source. Two observations he made support this hypothesis. One is
that large catches of tuna larvae were made at his leeward station where
strong trade winds (4-5 m/sec) tend to push surface waters away from shore.
The result is an upset in the hydrostatic equilibrium which could be
restored by upwelling. The second observation is that the thermocline,
which usually is at 100 m off Hawaii and which serves as a barrier to
vertical migration of larvae and vertical transport of water, was observed
to ascend the leeward slope off Kahe Point (Figure 16). Thus, it appears
likely that large numbers of tuna larvae will be upwelled at Kahe Point by
wind-driven currents from horizontal strata containing even higher
densities of larvae.

Miller (1974) reported on the results of studies on spatial
distribution of fish larvae in relation to variation in their abiotic
environment off Kauai, Oahu, and Maui. Chief among the mesopelagic
families found were Myctophidae and Gonostomatidae. Also found were
offshore pelagic families such as Scombridae, Molidae, and Gempylidae. The
20 most common families encountered in order of their percent overall
abundance were Myctophidae (16.3%), Blenniidae (13.9%), Gonostomatidae
(11.8%), Gobiidae (11.3%), Pomacentridae (8.9%), Tripterygiidae (6.7%),
Molidae (6.4%), Mullidae (3.5%), Apogonidae (3.3%), Carangidae (3.2%),
Scombridae (3.0%), Schindleriidae (2.3%), Exocoetidae (2.2%),
Tetraodontidae (1.4%), Gempylidae (0.5%), Coryphaenidae (0.5%),
Dussumieriidae (0.4%), Scorpaenidae (0.3%), Chlorophthalmidae (0.3%), and
Sphyraenidae (0.3%). Miller noted that 92% of all larvae collected
belonged to these 20 families and 54 other families were represented in the
samples.

C. Vertical Distribution

In a study conducted in the DCMES area, Hirota (1977) found that in
the neuston tows and shallow bongo net tows, species of interest to
commercial and sport fisheries included larvae of Scombridae,
Coryphaenidae, and Istiophoridae. Among midwater forms collected were
Myctophidae, Gonostomatidae, Gempylidae, Hemiramphidae, Exocoetidae,
Nomeidae, Carangidae, Scomberosocidae, and Labridae.

From deeper bongo net tows made below 200 m, Hirota found very few species compared with the neuston and shallow bongo net tow data. Those species present in the below 200-m tows also occurred in low concentrations.

Hirota concluded that (1) the neuston layer contains some species in very high abundance but which are rather uncommon in the 1-200 m layer, (2) the larvae of commercially important tunas occur more abundantly in the neuston layer than in the 1-200 m layer, (3) the species in the 1-200 m layer are primarily midwater forms, and (4) very few larval fish occur between 200 and 1,000 m.

D. Vertical Migration

Ichthyoplankton constitute a considerable proportion of the midwater plankton in tropical regions (Vinogradov 1968). In the 500-1,000 m layer, they constitute as much as 20-25% of the total mass of net plankton. In the middle latitudes, however, the picture changes considerably and the fish biomass in the deep layers is higher than in the tropical regions but its proportion in the plankton is considerably lower.

VI. OTHER IMPORTANT BIOLOGICAL RESOURCES

A. Endangered Species

Cumulative effects of commercial OTEC development may significantly impact threatened and endangered species. For example, migratory threatened and endangered species could emigrate from an area that becomes impacted from OTEC operation, thus possibly disrupting the animal's reproductive or feeding activities. Habitats could also be affected.

Payne (1979) reported that 22 marine mammal species may occur in Hawaiian waters including 2 mysticetes, 19 odontocetes, and one pinniped (Table 20). The humpback whale, _Megaptera novaengliae_, one of the most abundant cetaceans in Hawaii, is an endangered species which migrates into Hawaiian waters in winter to breed. A second endangered species, the Hawaiian monk seal, _Monachus schauinslandi_, is present in Hawaii; however, the population resides in the Northwestern Hawaiian Islands and away from potential OTEC sites.

Dolphins of _Stenella_, the most numerous small odontocetes in Hawaii, have been sighted in coastal areas throughout the island chain. Payne noted a 250-member population of spinner dolphins, _S. longirostris_, off Keahole Point, a potential OTEC area. The bottlenosed dolphin, _Tursiops_ spp., is also fairly common but the false killer whale, _Pseudorca crassidens_, and pygmy killer whale, _Feresa attenuata_, are less common.

The OTEC development in Hawaii is not expected to significantly impact threatened and endangered species.

B. Corals

Estimates are available of changes that have occurred in coral coverage near Kahe Point during the pre- and postconstruction phases of the offshore outfall for the Hawaiian Electric power plant. Beginning in 1973 and through 1977, the study showed that pronounced decline in coral coverage occurred as a result of general disturbances associated with outfall construction including underwater blasting, dredging, sedimentation, and turbidity. Decrease in coral coverage from 1978 to 1979, which approached the high values of earlier years, was highly significant compared with previous years. The rate of decline from 1980 to 1981 was 4.5-5.0 times the rate for the other years (Coles et al. 1982).

The drastic decrease in coral coverage at Kahe Point from 1979 to 1980, however, was not attributable to the operation of the outfall but to effects of a storm in January 1980. The storm waves generated at that time resulted in breakage of corals, scouring of reef surfaces by wave-suspended sand, and burial of living coral. Coles et al. concluded from their study that the detrimental effects of a single natural event were far more devastating than any stressful influences produced before or after the storm.

The results of the Kahe study also demonstrated that there has been no detrimental influence by the Kahe outfall on the coral. Coral decline has been greater with increased distance from the outfall. This pattern occurred rather consistently for all years examined except 1979 to 1980 when a significant correlation existed between changes in coral coverage and the outfall. In 1981, however, changes in total coral coverage were less negative at stations close to the outfall. In fact, Coles et al. concluded that there was an indication of a benign or even positive influence of the Kahe outfall on coral coverage or most of the Kahe reef in 1981.

The effects of thermal effluent on coral were investigated at Guam. At the Tanguisson Plant where the intake temperature varied between 26^C and 29°C and the discharge temperature between 30° and 34°C, there was significantly less coverage of the substratum by hermatypic corals along the reef margin near the thermal effluent than in areas outside its influence (Neudecker 1976), thus demonstrating that the thermal effluent has a negative effect on the coral community. Furthermore, the number of coral species, coral recruitment, and biomass accumulation were significantly less near the area of thermal effluent than in areas away from it.

VII. SUMMARY

This document presents a review of pertinent biological information characteristic of potential OTEC sites in the Pacific Ocean. Ideal ocean thermal resource can be found year round in the tropics between lat. 20°N and 20°S. Achieving maximum efficiency from an OTEC plant would require information on bottom topography and profile, magnitude of temperature change between surface and deep water, substrate, permanent water flow,

tidal, wind-driven, and inertial currents, mass transport, climatic conditions, benthic properties, and chemical properties of the sea water.

Some of the potential sites in the Pacific that meet temperature-depth requirements for OTEC operation include French Polynesia, New Caledonia, Guam, Hawaiian Islands, Japan, Philippine Islands, west coast of Mexico, and Taiwan. A Pacific plant ship site is also reviewed.

For open-ocean situations, data from OTEC-1 and DOMES are reviewed. Off Keahole where OTEC-1 experiments were conducted, the chlorophyll a concentration was low at the surface and ranged from 0.03 to 0.18 mg/m^3. A subsurface chlorophyll maximum, ranging between 0.17 and 0.62 mg/m^3 occurred between 64 and 94 m. Primary production ranged between 8.64 and 224.40 $mgC/m^2/day$. Compensation depth was estimated to be 125 m.

At the DOMES survey site, surface chlorophyll values averaged 0.117 mg/m^3. The CML was located deeper in summer (69 $\pm$ 24 m) than in winter (54 $\pm$ 30 m) but the difference was not significant. Primary production in the euphotic zone was 120 $mgC/m^2/day$ in summer and 144 $mgC/m^2/day$ in winter.

The composition of the phytoplankton community was similar at both oceanic sites. By order of importance in numbers, the groups included flagellates, dinoflagellates, diatoms, and coccolithophores; in terms of cell volume, the order of importance at the Keahole site was dinoflagellates, flagellates, diatoms, and coccolithophores.

Seasonal variation in phytoplankton standing crop was also reviewed. At the DOMES site, winter chlorophyll a concentrations were much higher than summer values.

In reviewing island sites, data collected during the Kahe survey off the Island of Oahu are reviewed. The CML was located rather deep, at 86 m, typical of more oceanic systems. Chlorophyll a concentration was 0.27 µg/liter. The primary productivity values reached 60.4 $\pm$ 25.6 $gC/m^2/yr$, typical of subtropical gyre water. Compensation depth 146 m.

The community composition in the Kahe environment was dominated by organisms ≤ 3 µm. Seasonal variation was observed in pigment levels, ATP values, and photosynthetic rates. The biomass, however, showed no significant seasonal changes.

Differences between open-ocean and island sites are also reviewed. Differences in the nature and magnitude of temporal variations are related to the physical environment. Variability in physical processes at Keahole produces a complex biological system, whereas at Kahe, the physical processes are less intense thus creating a more gradual and systematic temporal cycle.

Data from a plume survey conducted off Keahole Point were also reviewed.

Concerning zooplankton, investigators found that for open-ocean situations, the Keahole area was dominated by calanoid copepods, of which many species made extensive diel migrations. The biomass also showed significant seasonal changes. Biomass usually decreased from the surface to the deep strata.

Experiments during the plume survey off Keahole indicated total mortality of entrained zooplankton.

Biomass of zooplankton in the 0-200 m stratum at Keahole averaged 3.32 mg/m^3 on six cruises and 4.90 mg/m^3 on two later cruises; however, the difference in means was not significant. Zooplankton abundance usually changed with depth at the Keahole and DOMES sites, and concentrations were highest in the upper 150 m both day and night. Seasonally, the zooplankton off Keahole exhibited significant changes. Many species of zooplankton at Keahole made extensive diel migrations.

For the island site, it was found that zooplankton biomass in the Kahe environment varied by tenfold between shallow and deep tows; the shallow tows had the higher values. The biomass at night near the surface was also twice as great as that during the day. There is some evidence of zooplankton patchiness in the portion of the population making diel migrations. Off Kahe, copepods made up 73-85% of the total numbers of zooplankton. Among copepods, calanoids dominated: 38% of the day samples and 78% of the night samples.

Temporal variability of zooplankton abundance was not entirely seasonal off Kahe. Some animals in the zooplankton community (ostracods, euphausiids, and copepods), made vertical migrations; medusae, gastropod larvae, fish eggs, Foraminifera, and Corycacidae did not make vertical migrations.

A list of commercially important fishes caught off Keahole and Kahe Points in 1976-80 is presented, together with the mean annual catch and value. By far, the most important species are the pelagic tunas and billfishes. The nearshore fisheries are dominated by bigeye scads and mackerel scads and members of the snapper-grouper complex including jacks or crevalles. Species affected by the operation of an oil-fired electric generating plant at Kahe Point are also reviewed.

The benthic community near Kahe is extremely diverse; the pen shell, Atrina, predominated in some areas and spatangid heart urchins were numerous in other areas.

It was estimated that an OTEC plant would entrain 13.8 million m^3 of surface water per day and impact 1.38 million larvae. Additional studies, however, are required to make a critical evaluation of potential impact.

The nearshore waters off Kahe serve as spawning areas for a wide variety of fishes. The offshore waters may also be nursery grounds for some species.

At the DOMES site, the neuston layer contains some species in high
abundance but are rather uncommon in the 1-200 m stratum. Larvae of
commercially important tunas were abundant in the neuston layer. Species
found in the 1-200 m layer were primarily those associated with midwater
depths. Larval fish were uncommon between 200 and 1,000 m.

Studies conducted on impact of an existing oil-fired power plant's
outfall on corals in the Kahe environment indicates no detrimental effects.
Rather, decrease in coral coverage was mainly attributable to effects of
storms.

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Text Footnote

[1]C° is used to denote degree on a centigrade scale. °C is used to denote an actual reading.

[2]In an open-cycle system, the warm water is the working fluid. In a partial vacuum, the fluid is flash-evaporated and the resulting steam is driven across the turbine and thence to a heat exchanger where the vapor is condensed by the cold-water flow. The condensate is fresh water and is either discharged with the cold water or used for other purposes. In a closed-cycle system, warm water drawn from the surface provides heat which is transferred through a heat exchanger to a working fluid, for example, ammonia, Freon, propane, or other compounds. Enclosed in a partial vacuum, the working fluid is evaporated by the heat and the resulting high-pressure vapor drives a turbine to produce electricity. Cold water is then pumped from the deep layers to condense the low-pressure vapor in a second heat exchanger. The working fluid is then pumped back and recycled (Haven 1981).

[3]M. Takahashi, and P. Bienfang. Manuscr. in prep. Size structure of phytoplankton biomass and photosynthesis in subtropical waters.

TABLE 1. Summary of site parameters (from Wolff 1979a).

Site	Range distance (in km) to shore from 1,000 m	Monthly mean mixed layer depth meters	Monthly mean surface currents (cm/sec)	Sea state maximum percent of time >3 m	Number tropical cyclones per year
Sri Lanka	22–55	30–80	25–62	3	0.2–1.2
Mombasa	33–130	30–90	30–62	2	0.0–0.1
Jakarta	18–60	55–80	25–52	2	0.0–0.1
Dampier Land	265–417	30–80	25–47	4	0.4–1.2
Manila	6–82	20–80	30–52	5	4.0–6.0
Guam	7–18	60–120	30–47	5	2.0–3.0
Off Mexico	5–104	10–30	25–31	2	0.6–4.0
Plant ship Pacific	––	0–30	30–52	2	0.0–2.0
Ivory Coast	33–52	0–30	25–31	2	0.0–0.1
Plant ship Caribbean	––	40–110	30–62	3	0.6–1.2

TABLE 2. Summary of site parameters (from Wolff 1979a).

Site	Monthly mean temperature (°C) surface range	Monthly mean temperature (°C) 1,000 m	Annual mean ΔT (°C) 500 m	Annual mean ΔT (°C) 1,000 m	Coldest monthly mean ΔT (°C) 500 m	Coldest monthly mean ΔT (°C) 1,000 m
Sri Lanka	27.5-28.6	6.5-6.7	18.0	21.3	17.5	20.8
Mombasa N	25.4-28.7	7.2-7.5	17.0	19.5	15.6	18.2
Mombasa S	25.5-28.4	6.3-7.0	18.0	20.2	15.9	18.5
Jakarta	27.2-29.0	5.1-5.6	19.1	22.8	17.9	21.9
Dampier Land	25.6-28.2	4.9-5.0	19.1	22.6	17.4	20.7
Manila	27.1-29.5	4.4-4.6	20.0	24.0	18.6	22.6
Guam	27.7-29.2	4.3-4.4	21.1	24.1	20.4	23.4
Off Mexico	22.5-28.0	4.4-4.5	17.6	20.9	14.9	18.0
Plant ship Pacific	27.1-28.5	4.6-4.8	19.4	22.8	18.1	21.7
Ivory Coast	24.3-28.1	4.5	19.2	22.1	16.8	19.7
Plant ship Caribbean	26.4-28.4	5.0-5.3	18.1	22.4	17.2	21.3

TABLE 3. Number of phytoplankton species (mostly at the specific level) found in different studies of the Pacific Ocean (from Fryxell et al. 1979).

Reference	Location	Method	Diatoms	Dinoflagellates	Coccolithophorids	Other
Rampi 1952	Equatorial, 165°-175°W	Surface net tows	40	169	--	6
Hasle 1959	Equatorial, 145°W	Water samples	42	53	33	10
Smayda 1966	Inshore tropical waters, Gulf of Panama	Water samples	175	105	22	24
Venrick 1969	North of Hawaii, oceanic and neritic 155°W, between 26° and 56°N	Net and water samples	110	--	--	--
Marshall 1970	Peru Current, Ecuador to Gulf of Panama	Water samples	39	9	3	2
Marshall 1972	Galapagos Islands to Ecuador	Water samples	57	31	16	7
Semina 1974	Review of entire Pacific, oceanic and coastal	Net and water samples	272	683	48	21
Honjo and Okada 1974	155°W, off Alaska to west of Tahiti	Filtered water samples	--	--	90	--
Present study	DOMES area	Net and water samples	163	122	48	15

TABLE 4. Ten most abundant groups in order of decreasing abundance
determined by total number of cells counted in discrete
water samples collected during DOMES cruises 1975-76
(from Fryxell et al. 1979).

1.	Flagellates and monads
2.	_Gephyrocapsa_ _huxleyi_ (Lohm.) Reinhardt
3.	Gymnodiniaceae
4.	Yellow cells
5.	_Gephyrocapsa_ _oceanica_ Kamptner
6.	_Nitzschia_ _bicapitata_ Cleve
7.	_Oxytoxum_ _variable_ Schiller
8.	_Nitzschia_ _lineola_ Cleve
9.	_Nitzschia_ _closterium_ (Ehrenberg) Wm. Smith
10.	_Gephyrocapsa_ _ericsonii_ McIntyre and Bé

Table 5.--Phytoplankton species and abundance at potential OTEC sites. (from Johnson and Horne 1979).

Phytoplankton	Hawaii	Gulf	Puerto Rico
Diatoms	Rank	Rank	Rank
Amphiprora sp.	--	--	Rare
Asterionella sp.	--	--	Rare
Bacteriastrum			
delicatulum	Rare	--	--
B. elongatum	Rare	--	--
Bacteriastrum sp.	Rare	--	Rare
Chaetoceros			
coarctatus	Rare	--	--
C. convolutum	Rare	--	--
C. didymus var.			
anglica	--	Rare	--
C. lorenzianus	Rare	Dominant	--
C. messancase	Common	--	--
Chaetoceros sp.	Common	--	Rare
Climacodium			
frauenfeldianum	Rare	--	--
Coscinodiscus			
excentricus	Common	--	--
C. lineatus	Rare	Common	--
C. marginatus	Rare	--	--
Dactyliosolen			
mediterraneus	Dominant	--	--
Eucampia zoodiacus	Rare	--	--
Grammatophora sp.	--	--	Rare
Guinardia flaccida	--	Rare	--
Hemialus hauckii	Common	--	Rare
Hemiaulus sp.	Rare	--	Rare
Leptocylindrus			
danicus	Rare	Common	--
Licomorpha			
abbreviata	--	--	Rare
Licomorpha sp.	--	--	Rare
Mastogloia rostrata	Rare	--	--
Navicula carnifera	--	--	Rare
Navicula sp.	Dominant	--	Common
Nitzschia closterium	Dominant	--	Dominant
N. delicatissima	Rare	--	--
N. longissima	Rare	Rare	Rare
Nitzchia sp.	--	Dominant	Common
Planktoniella sol	Rare	--	--
Pleurosigma sp.	--	--	Rare
Pseudoeunatia			
deliolus	Rare	--	--
Rhizosolenia alata	Rare	--	--
R. bergonii	--	Rare	--
R. cylindrus	Rare	--	--
R. hebetata			
f. hiemalis	Rare	--	--
f. semispina	Rare	--	--
R. imbricata			
var. shrubsolei	Rare	--	Rare
R. styliformis	--	--	Rare
Surirella sp.	--	--	Rare
Synedra vaucheriae	Rare	--	--
S. undulata	Rare	--	--
Thalassionema			
nitzschioides	--	Rare	Common
Thalassiothrix			
frauenfeldii	--	Rare	Common
T. longissima	--	--	Common
Thalassiothrix sp.	--	--	Common
Unidentified pennate	Dominant	--	Common
Unidentified centric	Rare	--	--
Total number			
Diatom species	34	10	25

Phytoplankton	Hawaii	Gulf	Puerto Rico
Dinoflagellates	Rank	Rank	Rank
Amphidinium sp.	--	--	Rare
Ceratium fusus	Rare	--	--
C. incisum	Rare	--	--
C. karsteni	Rare	--	--
C. pentagonum	Rare	Rare	--
C. setaceum	Rare	--	--
Ceratium sp.	--	--	Rare
Cochlodinium sp.	Common	--	--
Dinophyris exigua	Rare	--	--
Dinophysis sp.	--	--	Rare
Exuviella apora	Rare	--	--
E. baltica	Rare	--	Common
E. compressa	Rare	Common	--
E. vaginula	--	Rare	--
Exuviella sp.	--	Common	Rare
Goniaulax sp.	Rare	--	Rare
Gymnodinium sp.	Rare	--	Rare
Gyrodinium sp.	Rare	--	--
Ornithocercus			
quadratus	--	Rare	--
Oxytoxum gigas	Rare	--	--
O. variabile	Rare	--	--
Parahistioneis sp.	--	--	Rare
Peridinium globulus	Rare	--	--
P. hirobus	Rare	--	--
P. pendunculatum	--	Common	Rare
P. tube	Rare	--	--
Peridinium sp.	Rare	--	Rare
Phalacroma ovum	Rare	--	--
Podolampas bipes	Rare	--	--
P. elegans	Rare	--	--
P. palmipes	Rare	Rare	--
Podolampas sp.	Rare	--	--
Pronoctiluca			
pelagica	--	--	Rare
Prorocentrum			
lebourae	Rare	--	--
P. micans	--	Common	--
Prorocentrum sp.	--	--	Rare
Protoerythropsis			
crassicaudata	Rare	--	--
Pyrocystis			
fusiformis	Rare	--	--
P. hamulus var.			
semicircularis	Rare	--	--
P. lunula	Rare	--	--
P. pseudonoctiluca	Rare	--	--
P. robusta	Rare	--	--
Unidentified			
athecate dino-			
flagellates	Dominant	--	Common
Total number			
Dinoflagellate			
species	33	9	14

Phytoplankton	Hawaii	Gulf	Puerto Rico
Blue-green Algae	Rank	Rank	Rank
Trichodesmium sp.	Rare	--	Dominant
Silicoflagellates	Rank	Rank	Rank
Dictyocha fibula	Rare	--	--
Ebria sp.	Rare	--	--
Coccolithophoroids	Rank	Rank	Rank
Discosphaera			
tubifer	Rare	--	--
Gephryocapso			
pcsamosa	Rare	--	--
Rhabdosphaera sp.	Rare	--	--
Umbellosphaera sp.	Common	--	--
Unidentified cocco-			
lithophorida	Common	--	Rare
Total number			
coccolitho-			
phorid species	5	0	1

TABLE 6. The natural range of phytoplankton density off Kahe Point, Oahu, based on the benchmark survey effort. The values represent 95% confidence limits for the depth-integrated parameters over the photic zone at two locations and over the area as a whole (from Noda et al. 1981b).

Parameter	Natural range at P = 0.05		
	Station 1	Station 2	Kahe Point
Chlorophyll-$\underline{a}$ ($mg \cdot m^{-2}$)	17.60–25.02	15.38–21.58	17.59–22.21
Phaeopigments ($mg \cdot m^{-2}$)	11.09–23.92	10.50–29.38	13.35–24.03
ATP ($mg \cdot m^{-2}$)	4.25–4.91	3.81–4.56	4.13–4.37
Photosynthesis ($mg\ C \cdot m^{-2} \cdot h^{-1}$)	6.53–15.54	10.73–22.35	10.23–17.35

TABLE 7. Criteria for detection of significant environmental change, based on a single benchmark data set. Detection limits (DL) given by $DL = t_{0.05}[S_1^2 + S_2^2)/2]^{1/2}$, where S_1^2 and S_2^2 are the mean square values for each source of variation at Stations 1 and 2, respectively (from Noda et al. 1981b).

Parameter	Level under examination	Source level for criteria	Detection limit at P = 0.05
Chlorophyll-a	Subsamples	Analytical	$0.03 \ \mu g \cdot l^{-1}$
	Hydrocasts	Subsamples	$0.31 \ \mu g \cdot l^{-1}$
	Stations	Hydrocasts	$0.64 \ \mu g \cdot l^{-1}$
	Time	Hydrocasts	$0.93 \ \mu g \cdot l^{-1}$
Phaeopigments	Subsamples	Analytical	$0.03 \ \mu g \cdot l^{-1}$
	Hydrocasts	Subsamples	$0.25 \ \mu g \cdot l^{-1}$
	Stations	Hydrocasts	$0.54 \ \mu g \cdot l^{-1}$
	Time	Hydrocasts	$2.54 \ \mu g \cdot l^{-1}$
ATP	Subsamples	Analytical	$0.25 \ ng \cdot l^{-1}$
	Hydrocasts	Subsamples	$13.92 \ ng \cdot l^{-1}$
	Stations	Hydrocasts	$16.64 \ ng \cdot l^{-1}$
	Time	Hydrocasts	$100.68 \ ng \cdot l^{-1}$
Photosynthesis	Hydrocasts	Subsamples	$0.16 \ \mu g \ C \cdot l^{-1} \cdot h^{-1}$
	Stations	Hydrocasts	$1.11 \ \mu g \ C \cdot l^{-1} \cdot h^{-1}$
	Time	Hydrocasts	$1.69 \ \mu g \ C \cdot l^{-1} \cdot h^{-1}$

TABLE 8. Comparison of phytoplankton parameters off Kahe Point (O'OTEC) and Keahole Point (HOTEC). The O'OTEC and HOTEC surveys included six cruises each and were conducted between May 1980–May 1981 and October 1978–December 1979, respectively. The upper limit of integration was 135 m (O'OTEC) and 250 m (HOTEC) for the biomass data, and 135 m (O'OTEC) and 120 m (HOTEC) for the photosynthetic data. The variation factor gives the ratio of the maximum/minimum range value, and the coefficient of variation $(10^2 \cdot s.d./\bar{X})$ is given in units of percent (from Noda et al. 1981b).

Comparison	Site	Phytoplankton Parameters			
		Chlorophyll a (mg·m⁻²)	Phaeopigments (mg·m⁻²)	ATP (mg·m⁻²)	Photosynthesis (mg C·m⁻²·h⁻¹)
Annual Range	O'OTEC	14.18 – 30.58	6.51 – 60.04	3.03 – 5.27	3.02 – 36.54
	HOTEC	14.64 – 44.45	4.07 – 15.07	0.84 – 5.58	0.72 – 18.70
Variation Factor	O'OTEC	2.2	9.2	1.7	12.1
	HOTEC	3.0	4.4	6.6	26.0
Annual Mean	O'OTEC	19.90	18.69	4.37	13.79
	HOTEC	24.56	11.81	3.06	8.79
Coefficient of Variation	O'OTEC	35	86	17	77
	HOTEC	43	54	59	89
Number of Hydrocasts	O'OTEC	36	36	36	36
	HOTEC	12	12	12	12

TABLE 9. Summary of conclusion drawn with respect to comparison of
phytoplankton parameters of the Keahole and Kahe environments.

Comparison	Conclusions
Chlorophyll <u>a</u> biomass	Similar at both sites; less overall temporal variation at Kahe.
Phaeopigment concentrations	At Kahe, higher in upper mixed layer and at subsurface maxima than at Keahole; depth of phaeopigment maximum corresponded with depth of chlorophyll maximum; pattern of temporal variability uniform with noteworthy increase only in August; degree of temporal variability 2.4X (excluding August); no significant relationship with primary production. At Keahole, depth of phaeopigment maximum deeper than chlorophyll maximum; phaeopigment stock showed considerable variability throughout year; temporal variability 4.4X; significant relationship found with primary production.
Phaeopigment: Chlorophyll <u>a</u> ratio	Higher at Kahe in mixed layer and at maximum.
Total microbial biomass	Higher at Kahe; mean ATP concentrations higher at Kahe in upper 100 m and in photic zone; total microbial biomass varied by a factor of 1.7 throughout year at Kahe but considerable variation experienced at Keahole; ATP concentrations highest from August to January at Kahe, erratic temporal variation over 14 months at Keahole with occasional extreme low values.
Photosynthetic rates	Greater at Kahe; pattern of variability showed less variability at Kahe. At Keahole, rates showed 26-fold variation; erratic changes throughout year, and extremely low production on occasions.

TABLE 10. Half-saturation constants (K_L) in terms of total irradiance during the incubation period, for the reference (non-enriched) carbon fixation profiles. The mean ($\pm$s.d.) K_L value from these trials was $3.86 \pm 1.19 \times 10^{20}$ quanta·m^{-2}; the mean ($\pm$s.d.) depth at which these values occurred was 40 ± 13 m (from Bienfang and Szyper 1982).

Experiment No.	Total irradiance at 1-2 m depth during incubation (10^{20} quanta·cm^{-2})	K_L (10^{20} quanta·cm^{-2})	Depth of K_L (m)
1	26.2	3.78	61
2	11.4	3.56	37
3	11.4	3.56	37
5	9.4	2.62	40
6	10.0	5.47	24

TABLE 11.   Biomass measures of zooplankton samples obtained during the
            HOTEC-12 plume survey including statistical tests of
            difference between means   (from Noda et al. 1981c).

	Sample No.	Dry weight (mg/m^3)	Ash-free dry weight (mg/m^3)	Percent ash $(\%)$
In plume	PSB1	3.30	2.23	33
	PSB2	3.65	2.21	39
	PSB3	2.94	2.01	32
	PSB4	3.71	2.31	38
	Mean $\bar{X}_p$	3.40	2.19	35.5
	s.d. $S_{\bar{x}}$	0.36	0.12	7.5
Out of plume	OPB1	4.86	3.69	25
	OPB2	5.27	3.91	26
	OPB3	5.37	4.20	22
	OPB4	5.99	4.72	21
	Mean $\bar{X}_o$	5.37	4.12	23.5
	s.d. $S_{\bar{x}}$	0.47	0.47	2.4
Statistical tests				
$\bar{X}_o - \bar{X}_p$		1.97	1.93	-12
t_{bdf}		6.71	*	-5.66
P (2 tailed)		<0.001	0.014	<0.01

*Variances were heterogeneous, P calculated by Fisher's exact
probability test.

TABLE 12. Macrozooplankton standing stocks as dry weight in mg/m² from daytime and nighttime bongo net profiles, each value being an integrated amount from 0 to 200, 200 to 1,000, or 0 to 1,000 m. Data are given for profiles at each station from Sites A, B, and C in 1975 and 1976. The ratios of these integrated stocks at night to that for the day (N/D ratio) are shown for each profile, and the dashes indicate no data (from Hirota 1977).

Site A

Depth	A-3° N Profile 1	A-3° N Profile 2	A+0° N Profile 1	A+0° N Profile 2	A+0° N Profile 3	A+0° N Profile 4	A+3° N Profile 1	A+3° N Profile 2
1975								
Day								
0-200 m	942	1054	960	913	1262	1427	681	809
200-1000 m	795	958	934	880	613	-	415	-
0-1000 m	1737	2012	1894	1793	1875	-	1096	-
Night								
0-200 m	864	639	2553	-	1086	1048	1872	1634
200-1000 m	531	548	607	516	-	-	-	-
0-1000 m	1395	1187	3160	-	-	-	-	-
N/D 1000 m ratio	0.80	0.59	1.67	-	-	-	-	-
N/D 200 m ratio	0.92	0.61	2.66	-	0.86	0.73	2.75	2.02
1976								
Day								
0-200 m	1880	2111	2051	2332	3943	2575	781	842
200-1000 m	540	388	904	521	1655	1248	576	496
0-1000 m	2420	2499	2955	2853	5601	3823	1357	1338
Night								
0-200 m	2386	3109	3669	3167	4766	5068	1437	1415
200-1000 m	295	377	396	443	629	453	444	465
0-1000 m	2681	3486	4065	3610	5396	5520	1881	1880
N/D 1000 m ratio	1.11	1.39	1.38	1.26	0.96	1.44	1.39	1.40
N/D 200 m ratio	1.27	1.47	1.79	1.36	1.21	1.97	1.84	1.68

TABLE 12. Continued.

	B-3° N Profile		Site B B+0° N Profile				B+0° N Profile	
Depth	1	2	1	2	3	4	1	2
1975								
Day								
0-200 m	1514	1236	2494	2627	2330	2553	956	843
200-1000 m	-	-	1210	1376	1196	954	-	-
0-1000 m	-	-	3704	4003	3126	3507	-	-
Night								
0-200 m	2981	2824	4089	5154	-	3311	1046	1101
200-1000m	847	2141	1244	948	1268	940	-	-
0-1000 m	3828	4965	5333	6102	-	4251	-	-
N/D 1000 m ratio	-	-	1.44	1.52	-	1.21	-	-
N/D 200 m ratio	1.97	2.28	1.64	1.96	-	1.30	1.09	1.31
1976								
Day								
0-200 m	-	2900	3421	2448	2839	2614	2853	2650
200-1000 m	-	-	1687	1143	1033	755	1351	996
0-1000 m	-	-	5108	3591	3872	3369	4204	3646
Night								
0-200 m	2790	2469	2920	2979	4252	3699	4172	4498
200-1000 m	520	-	1309	1354	1262	525	990	737
0-1000 m	3310	-	4229	4333	5514	4224	5162	5235
N/D 1000 m ratio	-	-	0.83	1.21	1.42	1.25	1.23	1.44
N/D 200 m ratio	-	0.85	0.85	1.22	1.50	1.42	1.46	1.70

TABLE 12. Continued.

	C-3° N Profile		C+0° N Profile				C+3° N Profile	
Depth	1	2	1	2	3	4	1	2
1975								
Day								
0-200 m	2035	1653	792	–	1624	1733	–	–
200-1000 m	1105	1126	–	–	663	910	859	813
0-1000 m	3140	2779	–	–	2287	2643	–	–
Night								
0-200 m	1898	2005	1902	1843	1303	1586	–	–
200-1000 m	824	771	–	–	378	587	–	–
0-1000 m	2722	2776	–	–	1681	2173	–	–
N/D 1000 m ratio	0.87	1.00	–	–	0.74	0.82	–	–
N/D 200 m ratio	0.93	1.21	2.40	–	0.80	0.92	–	–
1976								
Day								
0-200 m	7210	–	794	696	–	932	1577	1175
200-1000 m	–	–	566	387	915	436	–	–
0-1000 m	–	–	1360	1083	–	1368	–	–
Night								
0-200 m	–	5572	1538	1545	–	–	1967	1968
200-1000 m	–	–	111	123	298	246	–	–
0-1000 m	–	–	1649	1668	–	–	–	–
N/D 1000 m ratio	–	–	1.21	1.54	–	–	–	–
N/D 200 m ratio	–	–	1.94	2.22	–	–	1.25	1.67

Site C

TABLE 13. Zooplankton biomass in O'OTEC samples. All biomass values in mg/m^3 (from Noda et al. 1981b).

CRUISE 1
25-27 May 1980

Sample ID	Dry weight	Ash-free dry weight	% ash
1D25 A	4.67	3.05	35
1D25 B	3.31	1.80	46
1D200 A	3.88	2.58	34
1D200 B	2.70	1.63	40
1D600 A	1.35	1.00	26
1D1000 A	0.39	0.21	46
1N25 A	5.29	2.93	45

TABLE 14. Zooplankton biomass in O'OTEC samples. All biomass values in mg/m^3 (from Noda et al. 1981b).

CRUISE 2
10-11 August 1980

Sample ID	Dry Weight	Ash-free Dry Weight	% Ash	Carbon	Nitrogen	C:N Ratio	Carbon: Ash-free Ratio
1D25 A	10.6	5.34	50				
1D25 B	9.01	5.54	39	2.55	0.600	4.2	0.46
1D200 B	3.27	1.99	39				
1D600 A	2.03	1.49	27	0.71	0.160	·4.4	0.48
1D1000 A	1.05	0.51	51				
1N25 A	5.24	3.11	41				
1N25 B	3.48	2.25	35				
1N200 A	4.69	3.14	33				
1N200 B	3.72	2.73	27	1.04	0.240	4.3	0.38
1N600 A	0.54	0.36	33	0.17	0.038	4.5	0.47
2DNeu A	9.82	3.79	61	1.58	0.320	4.9	0.42
2D25 A	5.35	3.06	43				
2D25 B	6.08	3.07	50				
2D200 A	3.68	2.25	39	1.10	0.270	4.1	0.49
2D200 B	3.10	1.88	39				
2D600 A	0.81	0.58	28				
2D1000 A	0.41	0.21	49	0.10	0.019	5.3	0.48
2N25 A	16.7	9.84	41	4.51	0.990	4.6	0.46
2N25 B	15.8	9.17	42				
2N200 A	4.71	2.94	38				

TABLE 15. Zooplankton biomass in O'TEC samples. All biomass values in mg/m^3 (from Noda et al. 1981b).

CRUISE 3
5-6 November 1980

Sample ID	Dry Weight	Ash-free Dry Weight	% Ash	Carbon	Nitrogen	C:N Ratio	Carbon: Ash-free Ratio
1DNeu A	7.51	3.74	50				
1DNeu B	11.3	5.41	52	2.40	0.470	5.1	0.44
1D25 A	16.2	8.64	47				
1D25 B	19.3	10.4	46				
1D200 A	1.38	0.96	30				
1D200 B	2.72	1.56	43	0.70	0.160	4.4	0.45
1D600 A	1.21	0.81	33				
1D1000 A	0.63	0.42	33	0.21	0.044	4.9	0.51
1NNeu A	9.36	5.78	38				
1N25 A	15.6	9.61	38				
1N25 B	22.5	13.8	39	6.02	1.34	4.5	0.44
1N200 A	4.72	3.37	29				
1N200 B	4.13	3.02	27				
2DNeu A	4.58	1.72	62				
2DNeu B	6.52	2.39	63				
2D25 A	5.69	3.35	41	1.57	0.340	4.6	0.47
2D25 B	4.03	2.10	48				
2D200 A	3.87	2.78	28				
2D200 B	3.89	2.57	34				
2D600 A	1.14	0.89	22	0.42	0.100	4.2	0.47
2D1000 A	0.57	0.40	30				
2NNeu A	9.63	3.74	61	1.63	0.350	4.7	0.44
2NNeu B	3.55	2.21	38				
2N25 A	20.0	12.1	40				
2N25 B	14.0	9.96	29				
2N200 A	5.58	3.84	31	1.93	0.450	4.3	0.50
2N200 B	5.13	3.85	25				
2N600 A	2.18	1.79	18	0.78	0.190	4.1	0.44

TABLE 16. Zooplankton biomass in O'TEC samples. All biomass values in mg/m^3 (from Noda et al. 1981b).

CRUISE 4
10-11 January 1981

Sample ID	Dry Weight	Ash-free Dry Weight	% Ash	Carbon	Nitrogen	C:N Ratio	Carbon: Ash-free Ratio
1DNeu A	7.32	5.59	24				
1DNeu B	7.30	5.74	21				
1D25 A	5.67	3.75	34				
1D25 B	4.23	3.02	29	1.39	0.330	4.2	0.46
1D200 A	3.88	2.80	28				
1D200 B	3.35	2.27	32				
1D600 A	0.80	0.56	30				
1D600 B	0.82	0.65	21	0.33	0.068	4.9	0.51
1D1000 A	0.35	0.25	29	0.12	0.025	4.8	0.48
1NNeu A	38.8	25.0	36				
1NNeu B	28.0	20.2	28	10.3	2.07	5.0	0.51
1N25 A	12.0	9.43	21				
1N25 B	15.0	11.5	24				
1N200 A	2.33	1.80	23				
1N200 B	2.86	2.14	25	1.02	0.250	4.1	0.48
1N600 A	0.76	0.58	24				
2DNeu A	10.9	7.45	32	3.28	0.730	4.5	0.44
2DNeu B	10.2	6.84	33				
2D25 A	3.70	2.82	24				
2D25 B	4.61	3.42	26				
2D200 A	3.42	2.66	22				
2D200 B	3.58	2.74	23				
2D600 A	0.64	0.51	20				
2D600 B	0.64	0.48	25				
2D1000 A	0.18	0.14	22				
2NNeu A	11.1	8.18	26				
2NNeu B	13.7	9.14	33				
2N25 A	15.0	11.0	27	5.11	1.16	4.4	0.46
2N25 B	14.3	10.0	30				
2N200 A	5.31	4.19	21				
2N200 B	7.93	5.89	26				
2N600 A	0.92	0.66	28	0.32	0.069	4.6	0.48

TABLE 17. Zooplankton biomass in O'TEC samples. All biomass
values in mg/m^3 (from Noda et al. 1981b).

CRUISE 5
10-11 March 1981

Sample ID	Dry Weight	Ash-free Dry Weight	% Ash	Carbon	Nitrogen	C:N Ratio	Carbon: Ash-free Ratio
1DNeu A	3.24	2.22	31	1.25	0.230	5.4	0.56
1DNeu B	2.05	1.26	39				
1D25 A	3.59	1.61	55				
1D25 B	2.43	1.43	41				
1D200 A	1.13	0.89	21	0.40	0.096	4.2	0.46
1D200 B	3.44	2.64	23				
1D600 A	2.30	1.73	25				
1D600 B	1.84	1.41	23				
1D1000 B	0.43	0.34	21	0.18	0.032	5.6	0.53
1NNeu A	12.5	5.92	53				
1NNeu B	14.3	8.46	41				
1N25 A	8.32	4.65	44	2.02	0.480	4.2	0.43
1N25 B	7.72	4.47	42				
1N200 A	6.66	5.19	22				
1N200 B	5.10	3.82	25				
1N600 A	0.69	0.52	25	0.25	0.055	4.5	0.48
2DNeu A	1.76	0.63	64				
2DNeu B	1.22	0.45	63				
2D25 A	1.41	0.94	33				
2D25 B	1.83	1.11	39	0.50	0.110	4.5	0.45
2D200 A	4.20	3.21	24				
2D200 B	3.29	2.56	22				
2D600 A	1.58	1.21	23				
2D600 B	1.83	1.50	18	0.75	0.180	4.2	0.50
2D1000 A	1.07	0.87	19				
2NNeu A	12.5	5.61	55				
2NNeu B	10.7	5.31	50	2.32	0.480	4.8	0.44
2N25 A	6.66	4.73	29				
2N25 B	5.03	4.17	17				
2N200 A	8.48	6.55	23				
2N200 B	5.98	4.73	21	2.21	0.570	3.9	0.47
2N600 A	0.23	0.18	22				

TABLE 18. Zooplankton biomass in O'TEC samples. All biomass values in mg/m^3 (from Noda et al. 1981b).

CRUISE 6
27-28 May 1981

Sample ID	Dry Weight	Ash-free Dry Weight	% Ash	Carbon	Nitrogen	C:N Ratio	Carbon: Ash-free Ratio
1DNeu A	3.32	2.60	22				
1DNeu B	4.65	3.59	23				
1D25 A	4.20	3.24	23				
1D25 B	3.19	2.29	28	1.11	0.250	4.4	0.48
1D200 A	3.70	2.90	22				
1D200 B	3.14	2.46	22				
1D600 A	1.82	1.45	20	0.70	0.160	4.4	0.48
1D600 B	1.48	1.16	22				
1D1000 A	0.72	0.60	17				
1NNeu A	12.9	8.63	33	4.15	0.940	4.4	0.48
1NNeu B	13.7	9.22	33				
1N25 A	14.1	10.2	28				
1N25 B	18.0	12.6	30				
1N200 A	7.96	6.33	20	3.04	0.750	4.1	0.48
1N200 B	9.03	6.94	24				
1N600 A	0.90	0.70	22				
2DNeu A	2.18	1.29	41	0.65	0.087	7.4	0.50
2DNeu B	3.21	1.72	46				
2D25 A	5.05	3.45	32				
2D25 B	7.42	5.57	25				
2D200 B	3.98	2.95	26	1.38	0.340	4.1	0.47
2D600 A	0.63	0.45	29				
2D600 B	1.13	0.89	21				
2D1000 A	0.49	0.40	18	0.23	0.038	6.0	0.57
2NNeu A	12.6	7.45	41				
2NNeu B	16.3	11.2	31				
2N25 A	22.5	16.9	25				
2N25 B	15.9	12.2	23	5.94	1.47	4.0	0.49
2N200-A	7.19	5.47	24				
2N200 B	6.05	4.58	24				
2N600 A	0.88	0.67	24	0.34	0.078	4.4	0.51

TABLE 19. List of fishes at Keahole and Kahe Points and the annual mean catch and value as derived from catch reports of the Hawaii Division of Aquatic Resources, 1976-80.

Scientific name	English name	Local name	Keahole Point		Kahe Point	
			Catch (kg)	Value ($)	Catch (kg)	Value ($)
Thunnidae	Tunas	--	40	38	1	1
Katsuwonus pelamis	Skipjack tuna	Aku	28,098	42,422	164,058	215,755
Thunnus albacares	Yellowfin tuna	Ahi	385,865	1,002,672	14,899	40,490
Thunnus alalunga	Albacore	Ahipalaha	3,332	5,520	5	17
Thunnus thynnus	Bluefin tuna	Maguro	5,193	19,136	--	--
Thunnus obesus	Bigeye tuna	Ahi, menpachi	9,305	39,373	132	795
Euthynnus affinis	Kawakawa	Kawakawa	999	1,567	553	562
Istiophoridae	Billfishes	Au	6	7	--	--
Tetrapturus audax	Striped marlin	Au, naraigi	14,830	18,015	2,297	4,658
Makaira nigricans	Blue marlin	Au, kajiki	97,475	66,893	8,106	13,533
Xiphias gladius	Swordfish	Au ku	2,122	6,291	2	4
Istiophorus platypterus	Sailfish	Au lepe	312	389	11	--
Coryphaena hippurus	Dolphin	Mahimahi	14,421	54,228	3,339	16,502
Acanthocybium solandri	Wahoo	Ono	29,021	79,969	965	3,295
Epinephelus quernus	Sea bass	Hapuupuu	899	2,516	40	138
Seriola dumerili	Greater amberjack	Kahala	6,159	8,451	223	357
Pristipomoides sieboldii	Pink snapper	Kalekale	966	3,008	36	115
Caranx melampygus	Blue crevally	Omilu	20	51	109	299
Pristipomoides filamentosus	Pink snapper	Opakapaka	12,490	55,651	382	1,904
Aprion virescens	Gray snapper	Uku	6,541	25,446	156	524
Etelis carbunculus	Red snapper	Ehu	1,438	5,939	67	356
Etelis coruscans	Red snapper	Onaga	4,426	20,172	67	377
Carangidae	Jacks	Ulua	5,315	12,956	1,137	3,462
Mulloidichthys auriflamma	Red goatfish	Weke ulu	1,505	5,642	1,033	3,057
Bodianus bilunulatus	Spot wrasse	Aawa	151	103	10	9
Acanthurus achilles	Achilles tang	Pakuikui	8	9	--	--
Acanthurus dussumieri	Surgeonfish	Palani	378	368	526	453

TABLE 19. Continued.

Scientific name	English name	Local name	Keahole Point Catch (kg)	Value ($)	Kahe Point Catch (kg)	Value ($)
Scaridae	Parrotfish	Panuhunuhu	23	27	1	1
Scaridae	Parrotfish	Panunu	15	25	49	96
Gnathanodon speciosus	Yellow jack	Paopao	7	5	1	1
Myripristis chryseres	Squirrelfish	Pauu	112	294	--	--
Acanthurus xanthopterus	Surgeonfish	Pualu	238	308	188	173
Muraenidae	Eel	Puhi	20	24	262	96
Muraenidae	Black eel	Puhi-black	--	--	3	2
Conger cinereus	White eel	Tohe	9	18	63	35
Scaridae	Parrotfish	Uhu	739	1,436	137	236
Pristipomoides zonatus	Brigham's snapper	Gindai	144	428	9	36
Neomyxus chaptalii	False mullet	Ucuoa	198	736	1	1
Apogon kallopterus	Cardinalfish	Upapalu	95	195	--	--
Myripristis spp.	Squirrelfish	Uu, menpachi	3,916	13,490	315	1,254
Holocentridae	Squirrelfish	Uukanipo	36	27	1	1
Ruvettus pretiosus	Oilfish	Walu	6	1	3	2
Mulloidichthys samoensis	Goatfish	Weke	406	1,430	1,371	2,134
Alectis ciliaris	Threadfin jack	Ulua kihikihi	5	10	1	1
Lampris regius	Moonfish	--	1	1	2	7
Tetrapturus angustirostris	Shortbill spearfish	--	2,789	4,330	235	512
Makaira indica	Black marlin	Au	1,365	1,102	115	204
Parupeneus pleurostigma	Goatfish	Malu	6	18	71	179
Exocoetidae	Flyingfish	Malolo	1	1	--	--
Abudefduf abdominalis	Damselfish	Mamamo	19	50	175	430
Acanthurus sandvicensis	Convict tang	Manini	665	1,714	67	155
Elasmobranch	Shark	Mano	572	409	8	2
Sphyrna lewini	Hammerhead shark	Mano kihikihi	22	--	11	7
Etruneus micropus	Round herring	Makiawa	1	1	8	9

TABLE 19. Continued.

Scientific name	English name	Local name	Keahole Point Catch (kg)	Value ($)	Kahe Point Catch (kg)	Value ($)
Parupeneus multifasciatus	Goatfish	Moano	765	3,353	46	179
Polydactylus sexfilis	Threadfin	Moi	114	656	4	16
Mulloidichthys pflugeri	Red goatfish	Moilua	1	1	1	1
Monotaxis grandoculis	Porgy	Mu	40	141	98	340
Acanthurus olivaceus	Orange spot tang	Naenae	47	76	130	99
Kyphosus bigibbus	Rudderfish	Nenue	181	241	49	61
Scorpaenopsis cacopsis and S. gibbosa	Scorpionfish	Nohu	364	1,110	34	153
Aulostomus chinensis	Trumpetfish	Nunu	5	7	3	3
Alutera scripta	Filefish	Oililepe	--	--	226	429
Albula vulpes	Bonefish	Oio	77	92	948	2,025
Caranx mate	Jack	Omaka	3	16	2	6
Arothron hispidus	Balloonfish	Copuhue	--	--	45	3
Decapterus macarellus	Mackerel scad	Opelu	143,605	325,061	948	2,310
Anampses cuvieri	Spotted wrasse	Opule	--	--	3	7
Zebrasoma flavescens	Yellow tang	Pala	2	6	--	--
Bothus mancus and B. pantherines	Flounder	Paki'i	3	5	3	2
Belonidae	Needlefish	Ahaha	3	2	5	7
Kuhlia sandvicensis	Mountain bass	Aholehole	49	206	44	181
Selar crumenophthalmus	Bigeye scad	Akule	6,914	12,669	6,887	17,422
Selar crumenophthalmus	Small bigeye scad	Hahalalu	858	1,300	3,435	7,798
Holocentridae	Squirrelfish	Alaihe	259	805	5	12
Mugil cephalus	Mullet	Anaama	101	456	47	252
Chanos chanos	Milkfish	Awa	251	338	243	614
Elops hawaiiensis	Ten pounder	Awaawa	1	1	29	60
Priacanthidae	Red bigeye	Aweoweo	1,399	3,438	42	100
Labridae	Wrasses	Fa	1	1	1	1
Scaridae	Parrotfish	Hanui	132	313	2	3
Gempylus serpens	Snake mackerel	Hauliuli	149	240	--	--

TABLE 19. Continued.

Scientific name	English name	Local name	Keahole Point Catch (kg)	Keahole Point Value ($)	Kahe Point Catch (kg)	Kahe Point Value ($)
Dasyatidae	Ray	Hihimanu	8	8	--	--
Labridae	Wrasses	Hinalea	3	2	4	1
Balistidae	Triggerfish	Humuhumu	75	74	67	84
Hemiramphidae	Halfbeak	Iheihe	4	3	--	--
Sphyraena barracuda	Barracuda	Kaku	535	761	78	115
Naso unicornis	Surgeonfish	Kala	215	163	732	588
Elagatus bipinnulata	Rainbow runner	Kamano	418	608	12	8
Sphyraena helleri	Japanese barracuda	Kawelea	534	1,032	17	27
Ctenochaetus strigosus	Surgeonfish	Kole	73	122	2	5
Parupeneus porphyreus	Red goatfish	Kumu	415	2,755	323	1,896
Abudefduf sordidus	Damselfish	Kupipi	14	33	--	--
Cheilio inermis	Mongoosefish	Kupoupou	4	10	1	1
Xyrichthys pavo	Razorfish	Laenihi	64	300	2	12
Scomberoides lysan	Leatherback	Lai	18	36	3	7
Aphareus rutilans	Snapper	Lehi	1,933	5,783	11	51
Acanthuridae	Surgeonfish	Maiii	19	31	1	1
Acanthurus nigroris	Surgeonfish	Maiko	189	346	1	1
Scomber japonicus	Chub mackerel	Saba	18	16	1	1
Decapterus macarellus	Mackerel scad	Opelu mama	1	1	--	--
Cichlidae	Tilapia	--	13	38	3	7
Lutjanus kasmira	Blue-line snapper	Taape	1,679	2,461	1,687	1,991
Lutjanus vaigiensis	Red-green snapper	Toau	18	101	1	1
Cephalopholis argus	Sea bass	Roi	29	163	--	--
Cirrhitidae	Hawkfish	Poopaa	3	9	--	--
Brachyura	Crab	Papai	30	164	38	62
Ranina ranina	Frog crab	Kona crab	343	1,557	27	15
Portunus sanguinolentus	White crab	Kuahonu	--	--	37	7
Podophthalmus vigil	Red crab	Moala	26	287	16	60
Scylla serrata	Mangrove crab	Samoan	2	-	1	1
Penaeus marginatus	Shrimp	Opae	129	809	--	--
Panulirus marginatus and P. penicillatus	Spiny lobster	Ula	50	2,403	168	941

TABLE 19. Continued.

Scientific name	English name	Local name	Keahole Point		Kahe Point	
			Catch (kg)	Value ($)	Catch (kg)	Value ($)
Scyllarides squammosus and S. haani	Slipper lobster	Ulapapapa	2	--	6	23
Octopoda	Octopus	Hee, tako	136	633	344	1,078
Decapoda	Squid	Muhee	109	177	--	--
Helcioniscus exaratus and H. argentatus	Limpet	Opihi	598	2,502	--	--
Centrechinus paucispinus	Sea urchin	Wana	--	--	1	--
Holothuridae	Sea cucumber	Namako	1	2	30	183
Rhodophyta and Chlorophyta	Seaweed	Limu	--	--	1,220	2,118
Miscellaneous	--	--	2,147	5,614	145	247
Total			807,914	1,882,450	219,510	353,853

TABLE 20. Marine mammals of the Gulf of Mexico and Hawaii (from Payne 1979).

Species	Gulf of Mexico	Hawaii
Order Sirenia		
Family Trichecidae		
*Trichechus manatus, West Indian manatee	common inshore	—
Order Carnivora, Suborder Pinnipedia		
Family Phocidae		
*Monachus shauinslandi, Hawaiian monk seal	—	Common away from OTEC sites
*M. tropicalus, Caribbean monk seal	extinct?	—
Family Otariidae		
Zalophus californianus, California sea lion	Rare, introduced	—
Order Cetacea, Suborder Mysticeti		
Family Balaenidae		
*Balaena glacialis, Black Right whale	Rare	—
Family Balaenopteridae		
Balaenoptera acutorostrata, Minke whale	Rare	—
B. borealis, Sei whale	Rare	—
B. edeni, Bryde's whale	Rare	Occasional
*B. musculus, Blue whale	Rare	?
*B. physalus, Fin whale	Rare	?
*Megaptera novaeangliae, Humpback whale	—	—
Suborder Odontoceti		
Family Delphinidae		
Delphinus delphis, Common dolphin	Fairly common	Fairly common†
Feresa attenuata, Pygmy killer whale	Rare	Fairly common
Globicephala macrorhyncus, Short-finned pilot whale	Rare	Rare

Species	Gulf of Mexico	Hawaii
Grampus griseus, Risso's dolphin	Rare	Rare
Lagenodelphis hosei, Shortsnouted whitebelly dolphin	—	Rare
Orcinus orca, Killer whale	Rare	—
Peponocephala electra, Little blackfish	—	Rare
Pseudorca crassidens, False killer whale	Fairly common	Fairly common
Stenella attenuata, Spotted dolphin	—	Fairly common
S. coeruleoalba (= S. styx), Striped dolphin	Fairly common	Fairly common
S. frontalis (= S. clymene, bridled dolphin	Fairly common	—
S. longirostris, Spinner dolphin	Rare	Common
S. plagiodon, Spotted dolphin	Common	Rare
Steno bredanensis, Roughtoothed Dolphin	Rare	Rare
Tursiops gilli, Pacific bottlenosed dolphin	—	Fairly common
Tursiops truncatus, Bottlenosed dolphin	Common	Fairly common
Family Physeteridae		
Kogia breviceps, Pygmy sperm whale	Common inshore in western Gulf	Rare
K. simus, Dwarf sperm whale	Rare	Rare
*Physeter catodon, Sperm whale	Fairly common in past, now rare	Occasional
Family Ziphiidae		
Mesoplodon densirostris, Densebeak whale	—	Rare
M. europaeus, Gulfstream beaked whale	Rare	—
Ziphius cavirostris, Goosebeak whale	Rare	Rare

*Denotes endangered or threatened species.
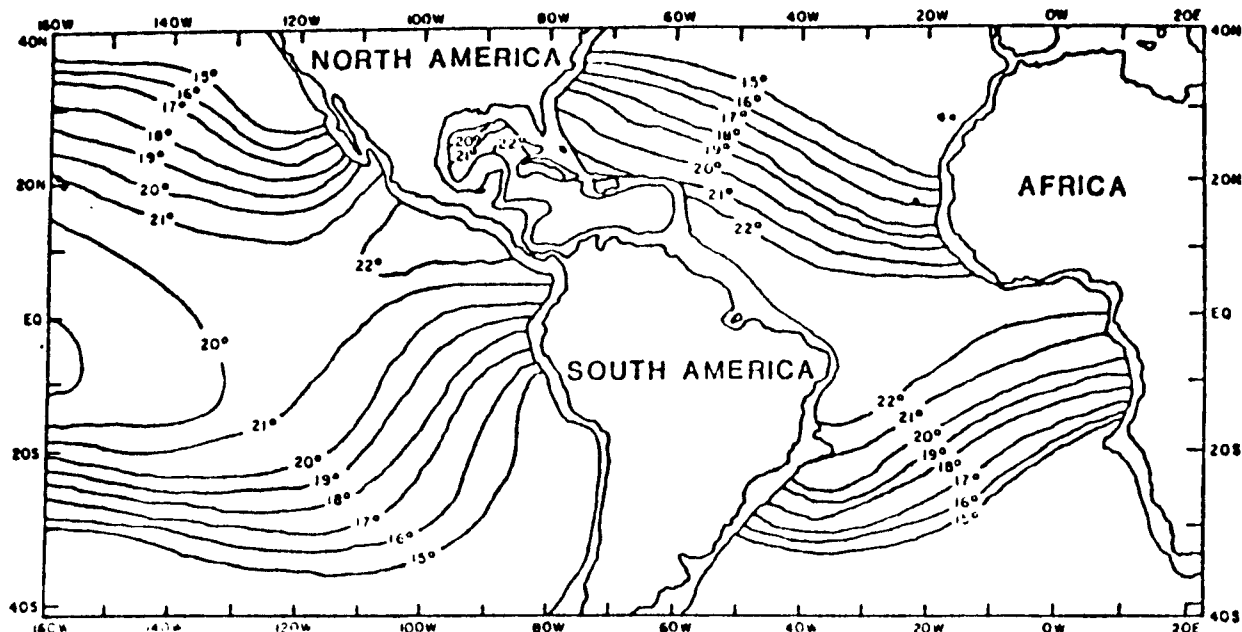
Figure 1.--The OTEC thermal resource--ΔT (°C) between surface and 1,000 m depth (from Yuen 1981).
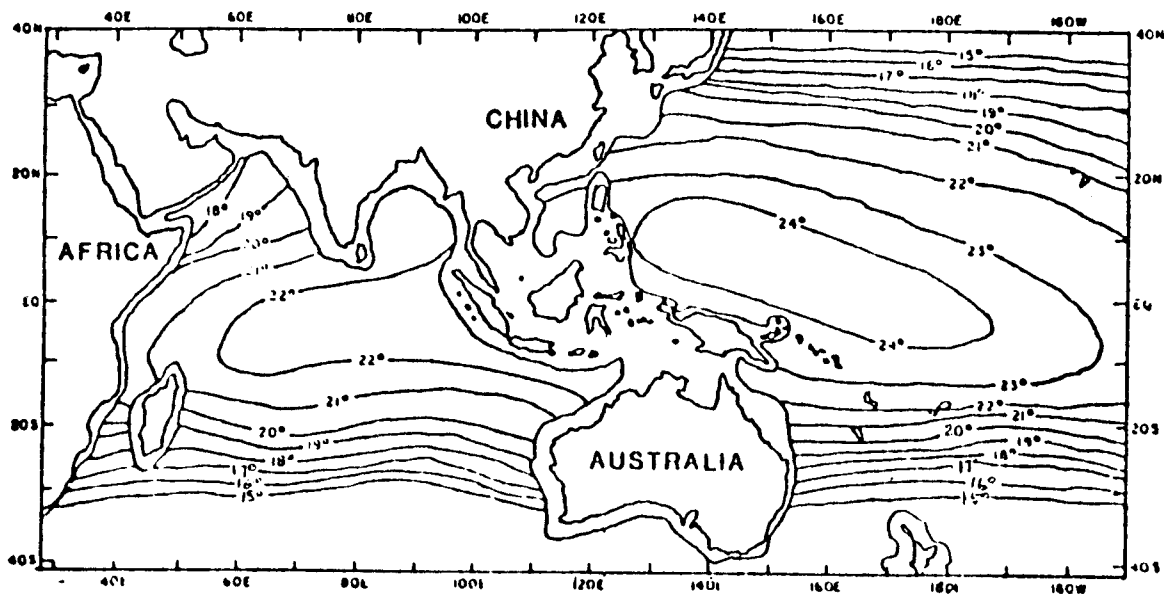
Figure 2.--The OTEC thermal resource--ΔT (°C) between surface and 1,000 m depth (from Yuen 1981).
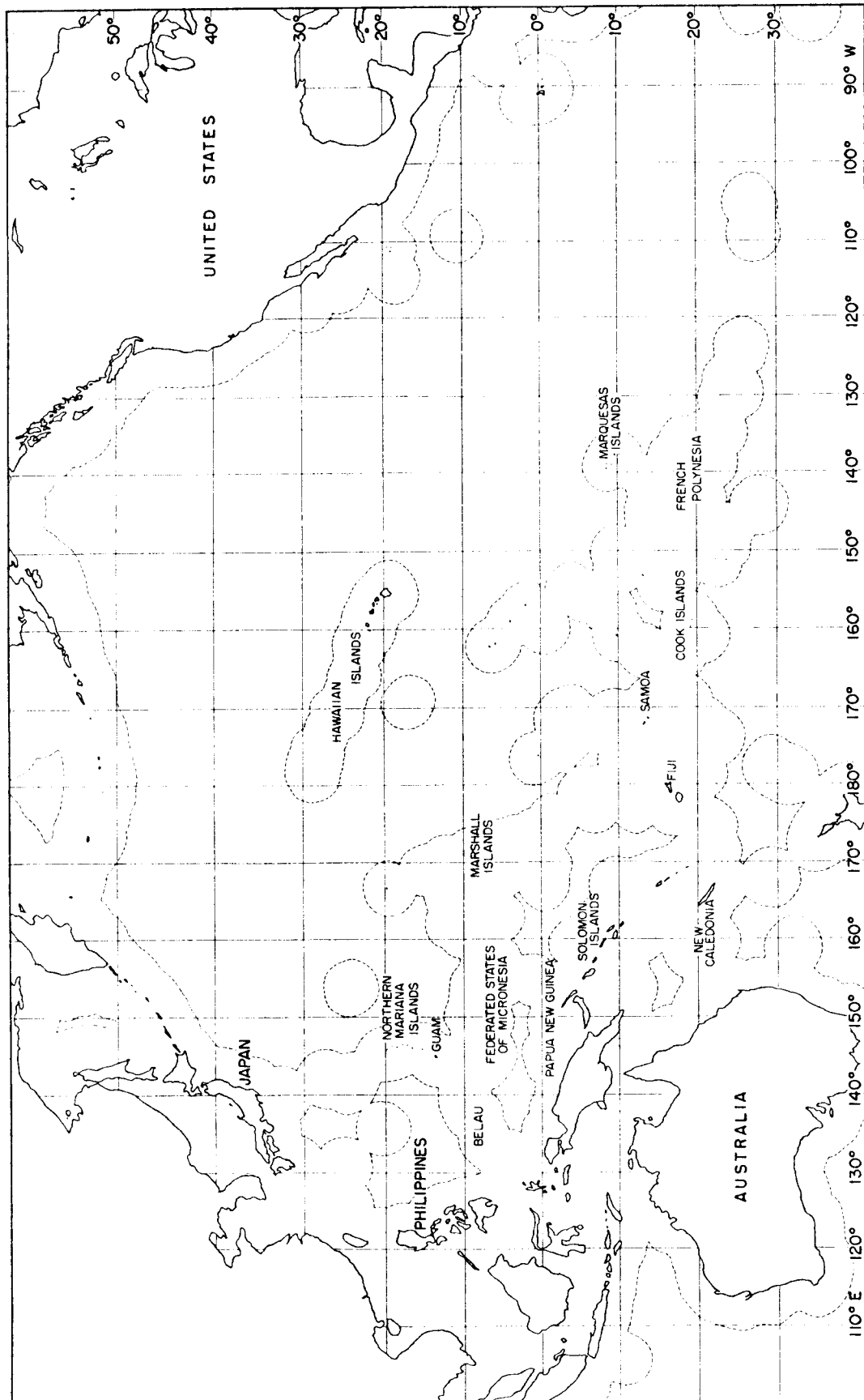
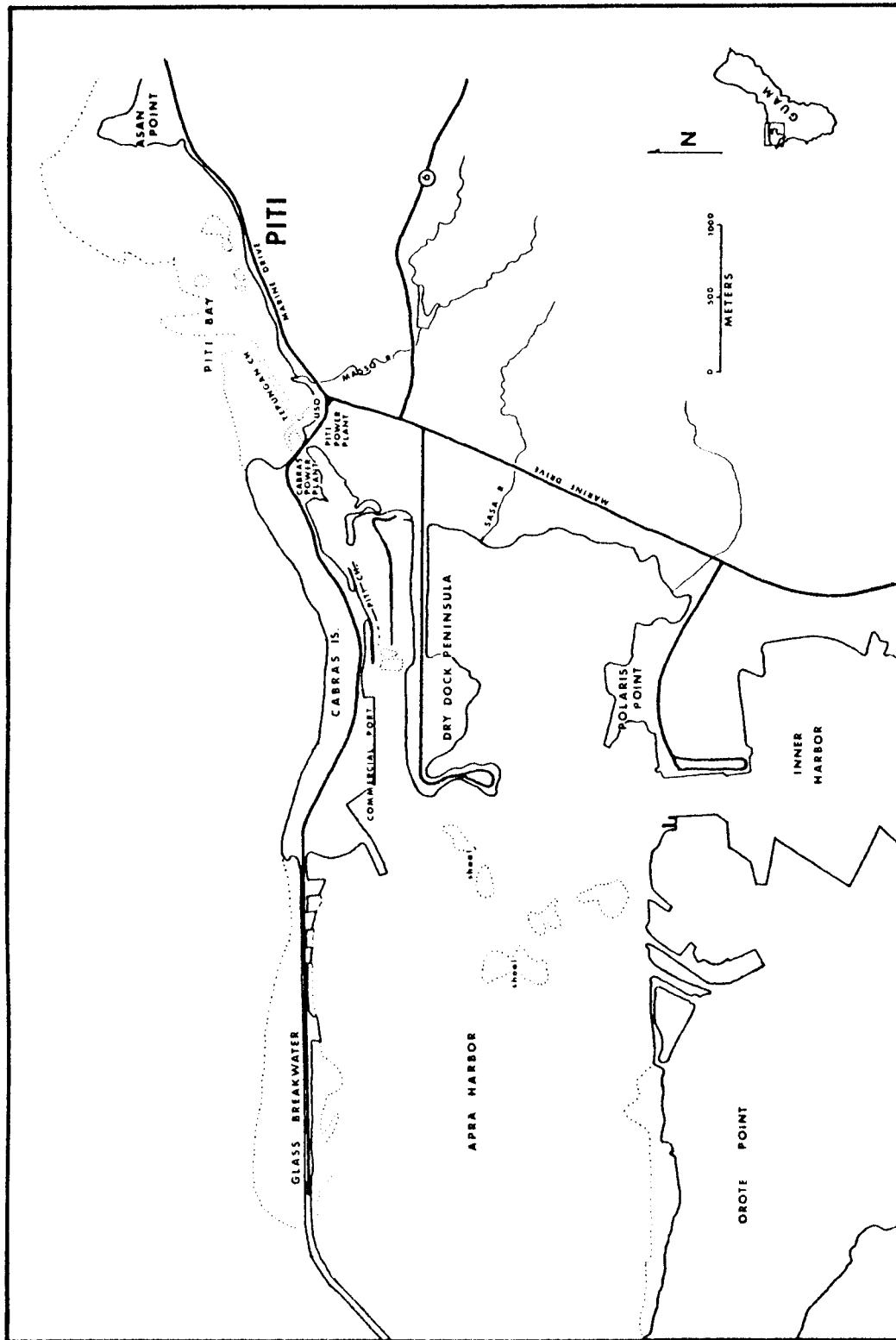Figure 3.--Economic boundaries of Pacific Basin countries between lat. 40°N and 30°S.

Figure 4.--Geographic setting of study area for potential OTEC development on Guam (map adapted from Marsh and Doty 1976).
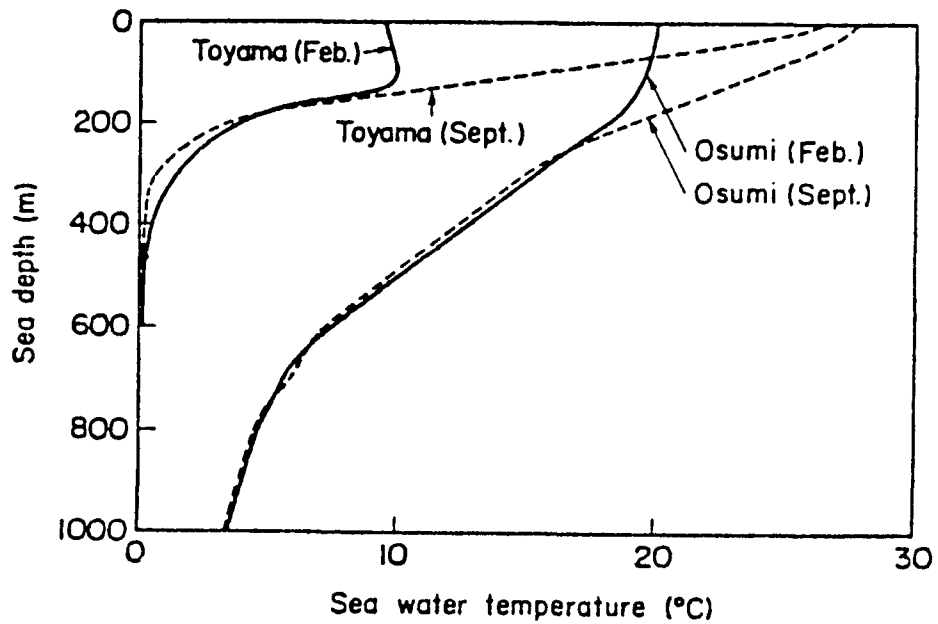
Figure 5.--Maximum (Sept.) and minimum (Feb.) of monthly average of sea temperature at offshore of Osumi Island (Pacific Ocean) Toyama Bay (Japan Sea) (Homma and Kamogawa 1979).
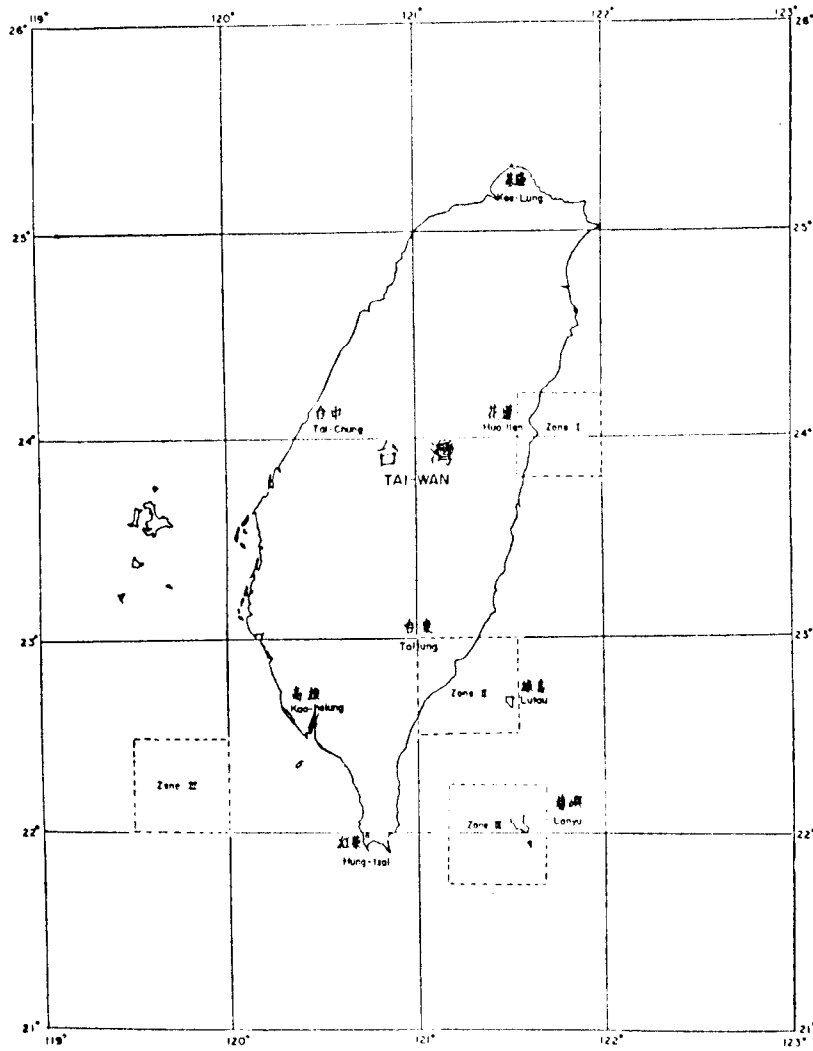
Figure 6.--Geographic setting of study area for potential OTEC development on Taiwan (Liang et al. 1981).

Figure 7.--The OTEC-1 site location off Keahole Point, Hawaii.
(from Noda et al. 1981b).
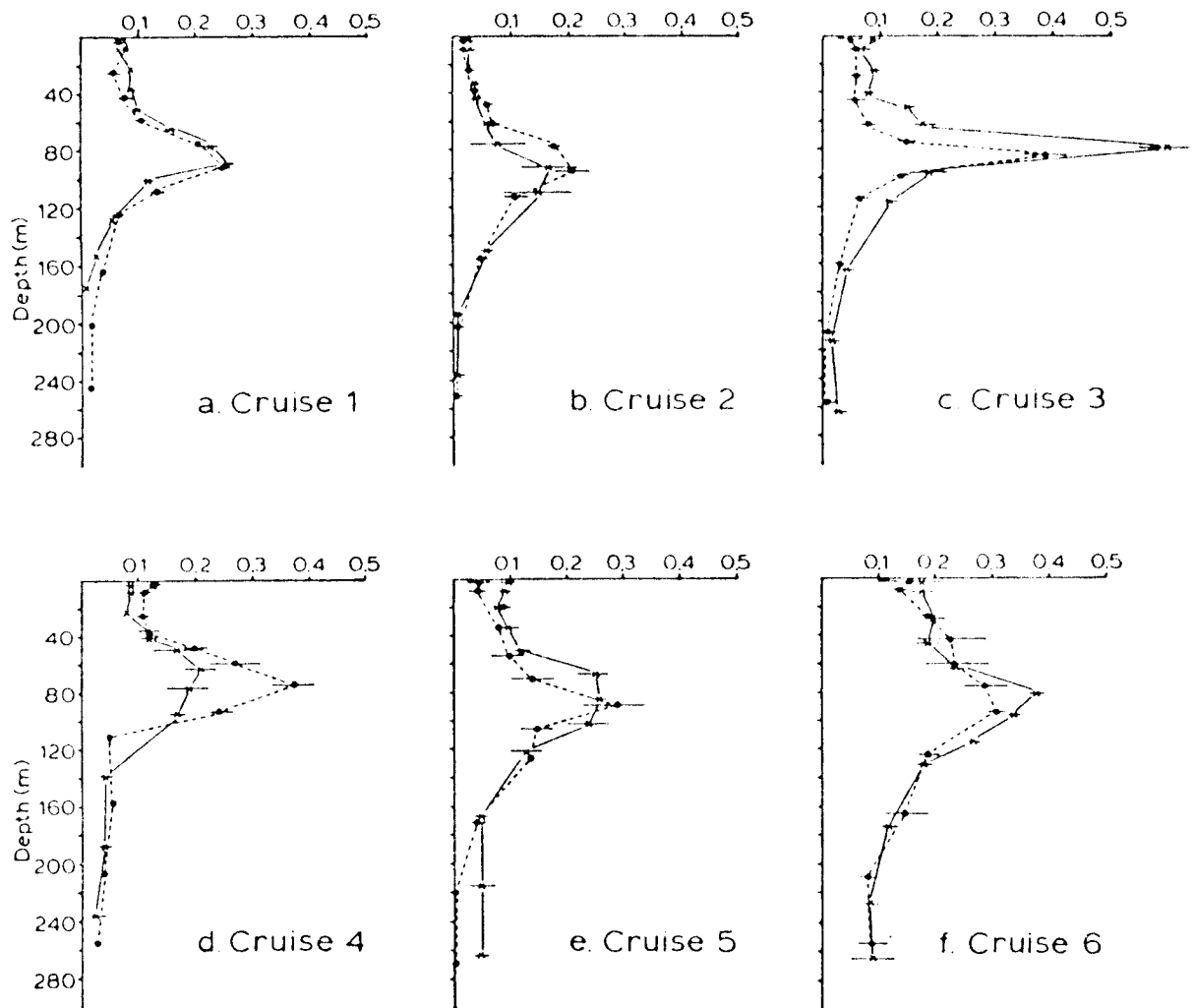
Figure 8.--Vertical profiles of chlorophyll a concentrations (mg·m^{-3}) in the water column at the HOTEC site. The "dawn" hydrocasts are represented by the dotted-line plots, and "dusk" hydrocasts by the solid-line plots. The horizontal bars indicate the standard deviations about the means of triplicate analyses (Noda et al. 1980).
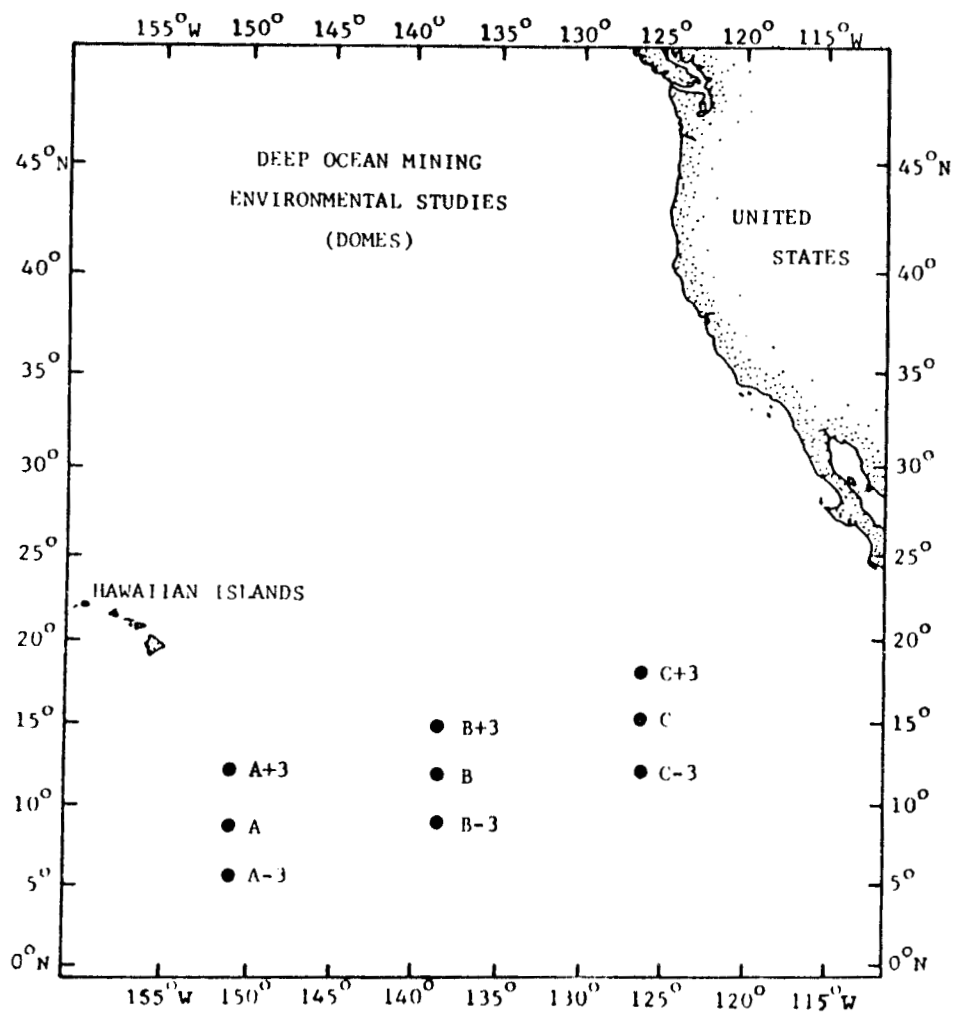
Figure 9.--Stations with discrete water samples analyzed quantitatively in this study from collections made in fall (1975) and spring (1976) (Fryxell et al. 1979).
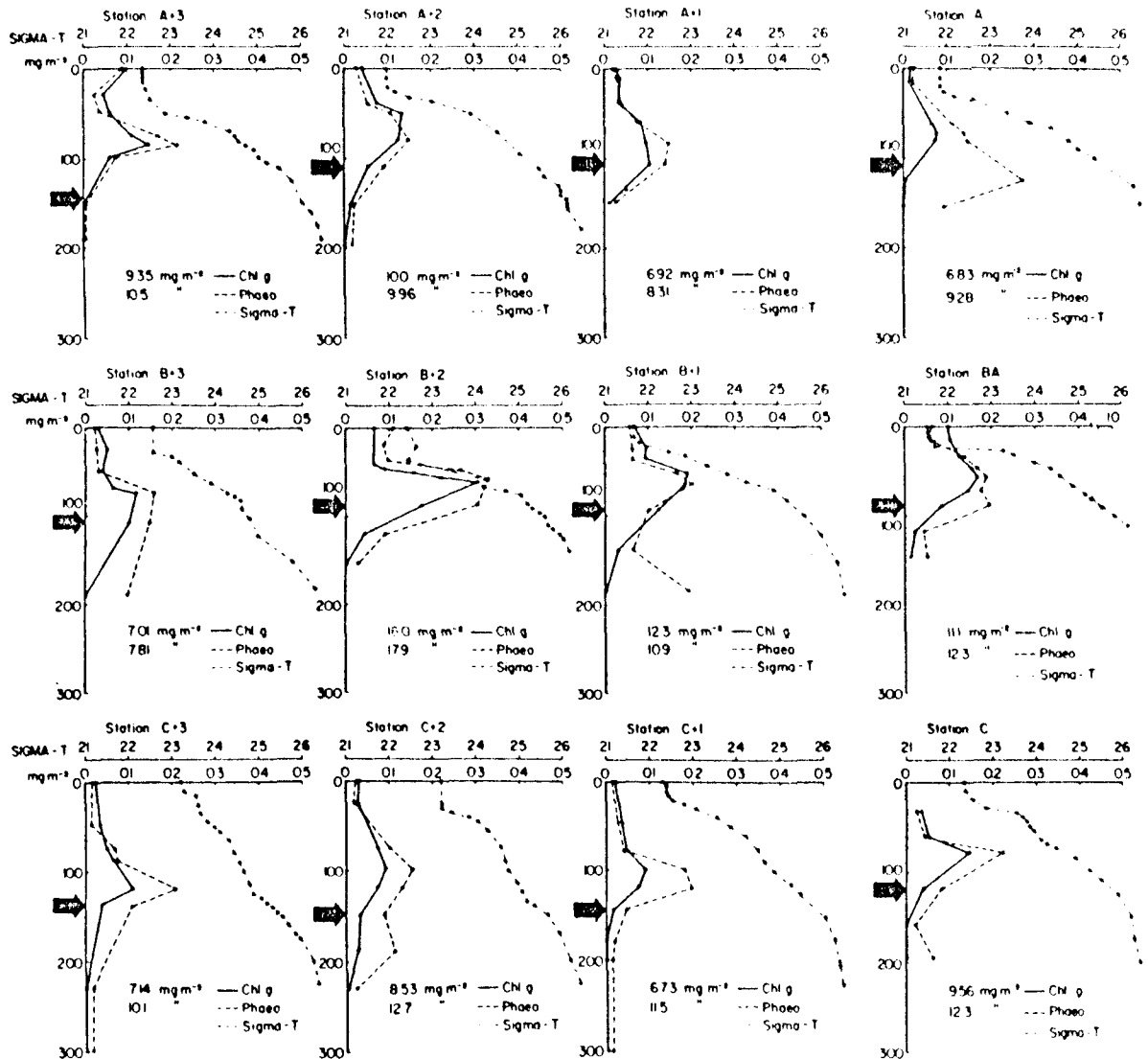
Figure 10.--Vertical distribution of chlorophyll a and phaeopigments concentrations with sigma-t at the stations occupied in the three transects A, B, and C in the summer of 1975. Depth (m) of the euphotic zone is shown by arrows (El-Sayed and Taguchi 1979).
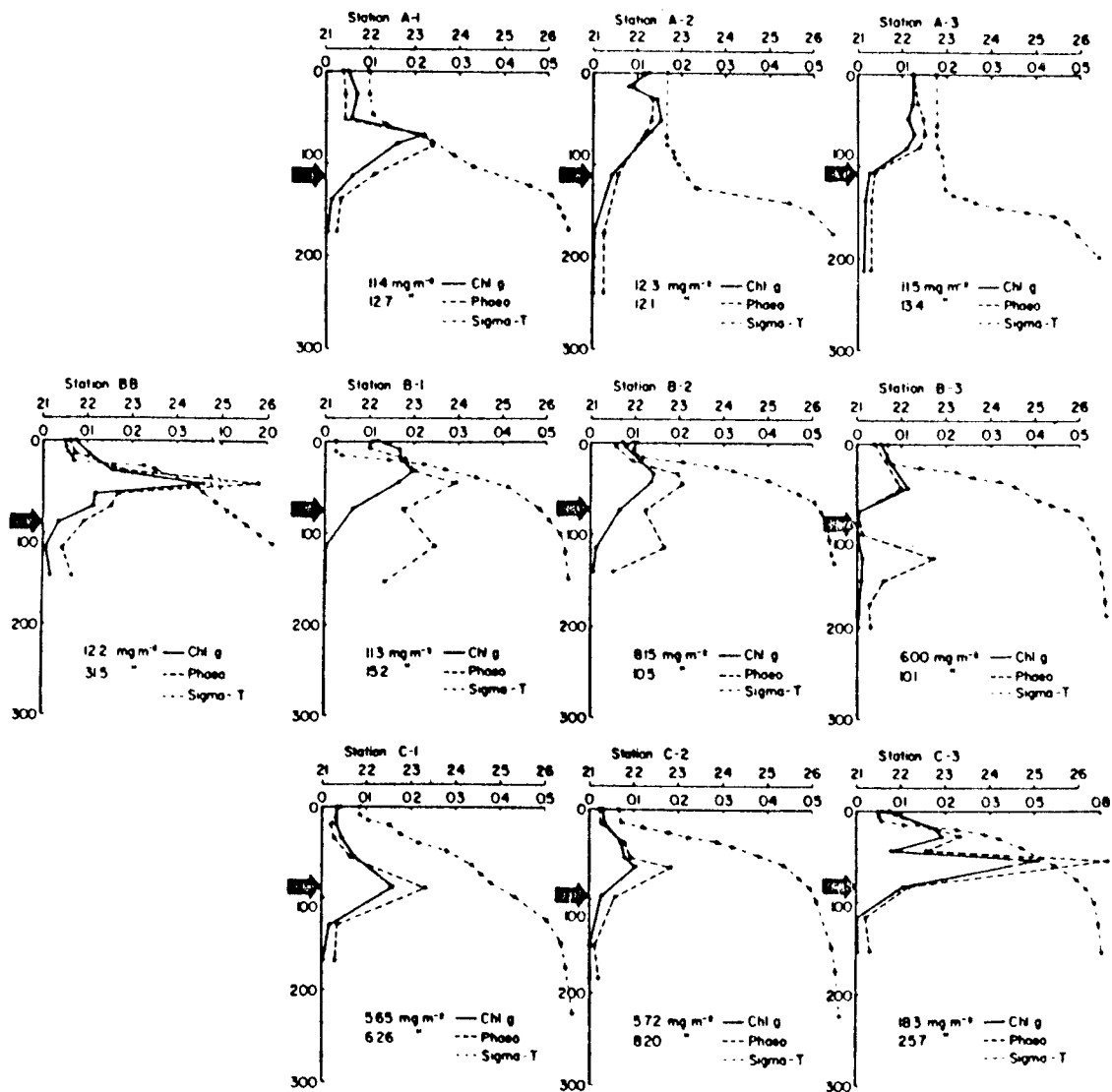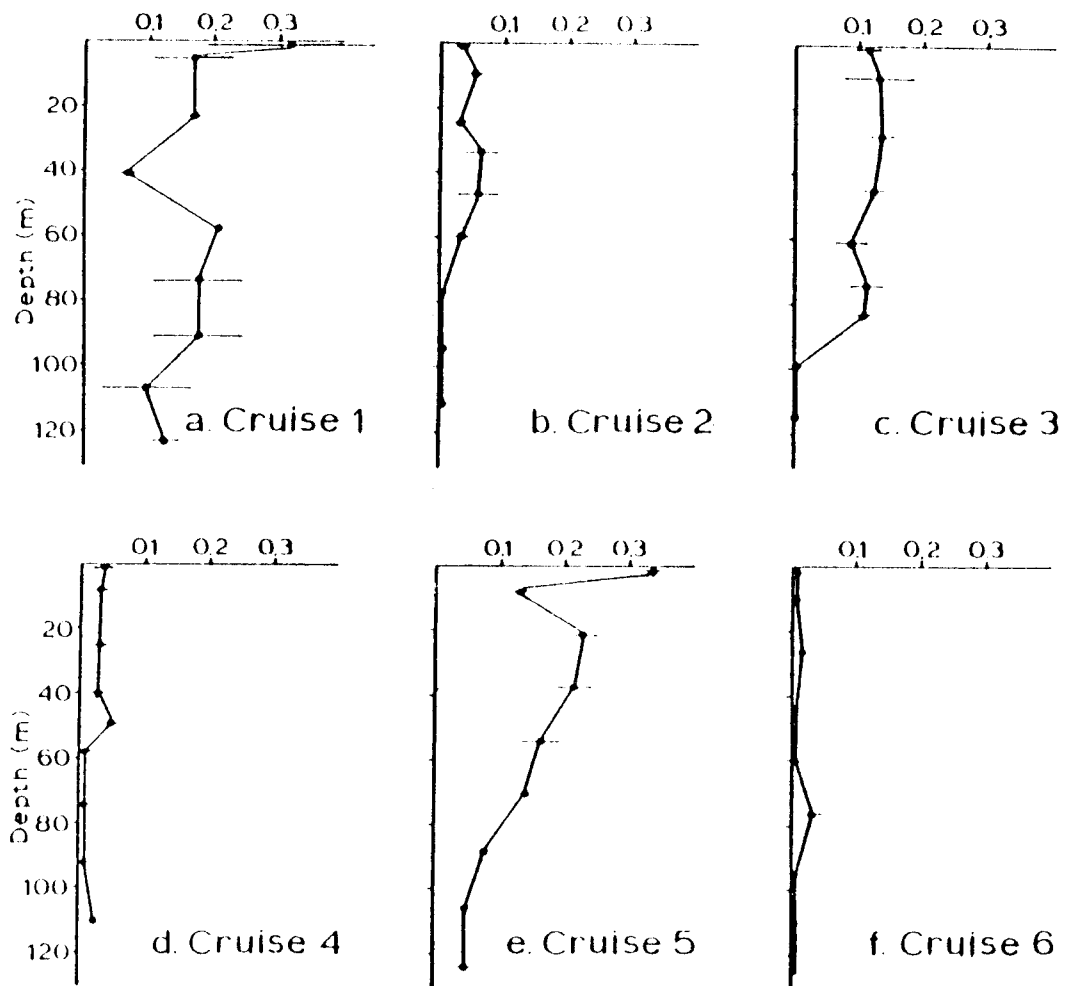
Figure 10.--Continued.
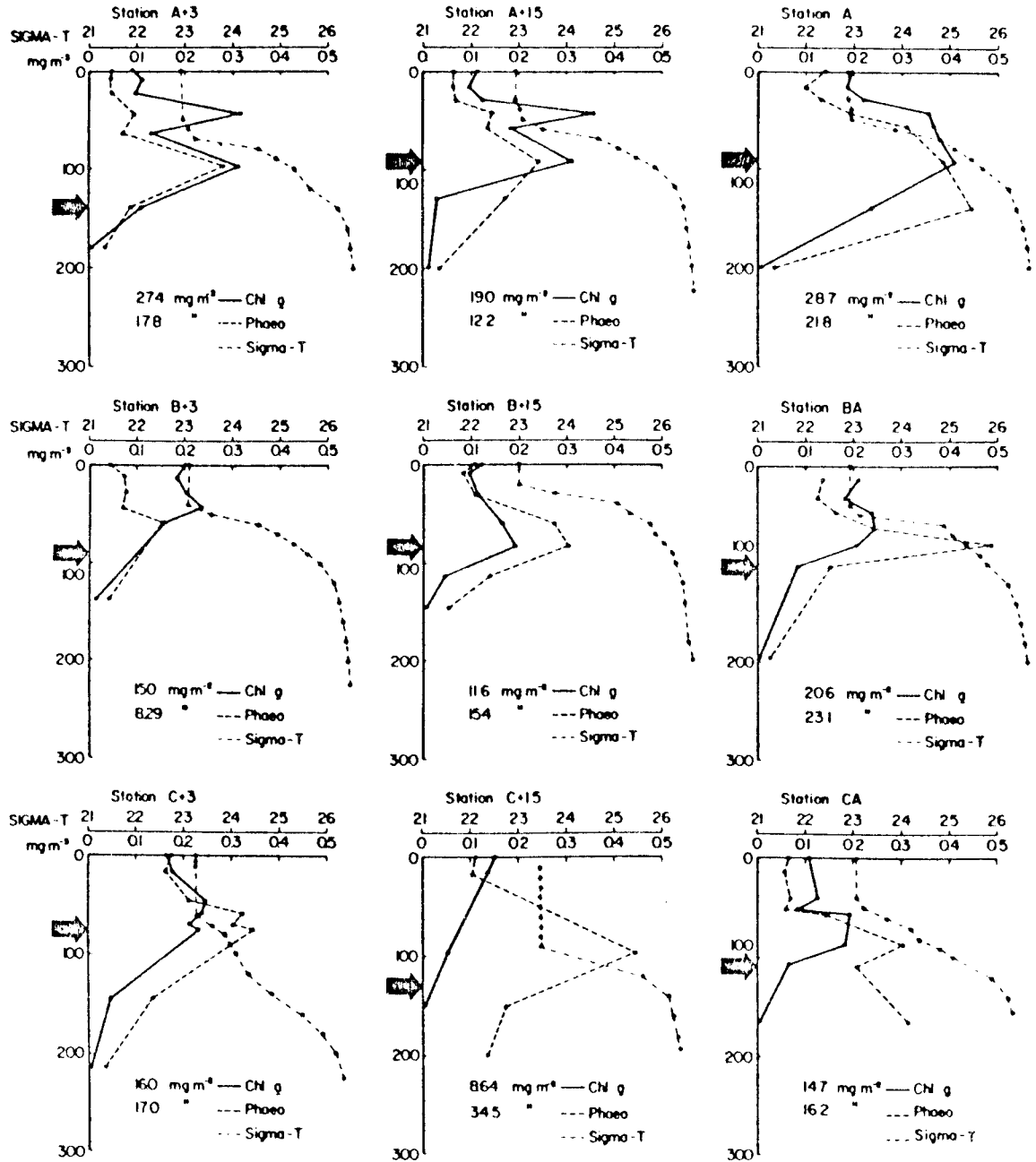
Figure 11.--Vertical distribution of chlorophyll a and phaeopigments concentrations with sigma-t at the stations occupied in the three transects A, B, and C in the winter of 1976. Depth (m) of the euphotic zone is shown by arrows (El-Sayed and Taguchi 1979).
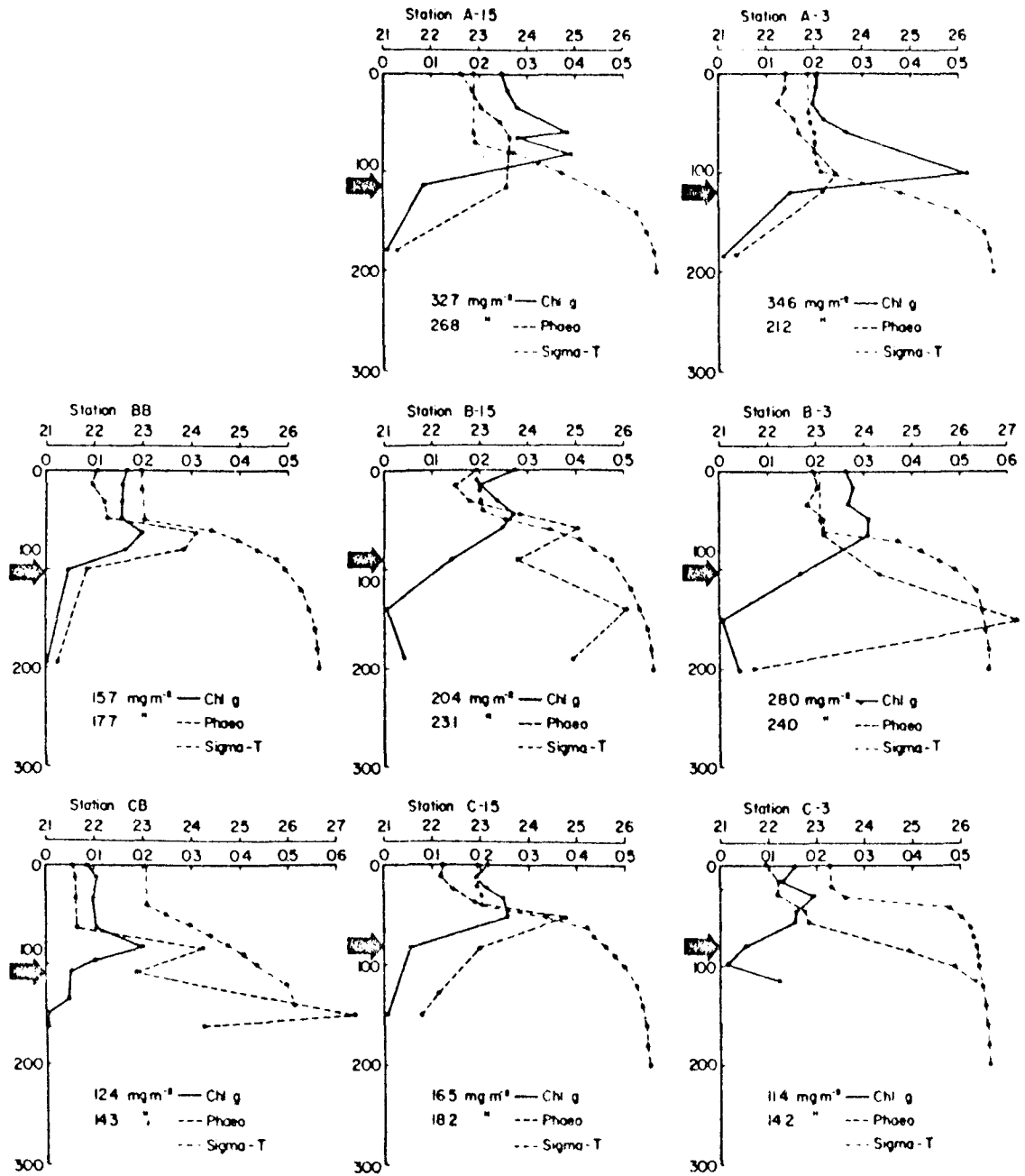
Figure 11.--Continued.

Figure 12.--Vertical profiles of the rates of primary production ($mg\ C \cdot m^{-3} \cdot h^{-1}$) at the HOTEC site. The horizontal bars indicate the standard deviations about the means of triplicate analyses (Noda et al. 1980).
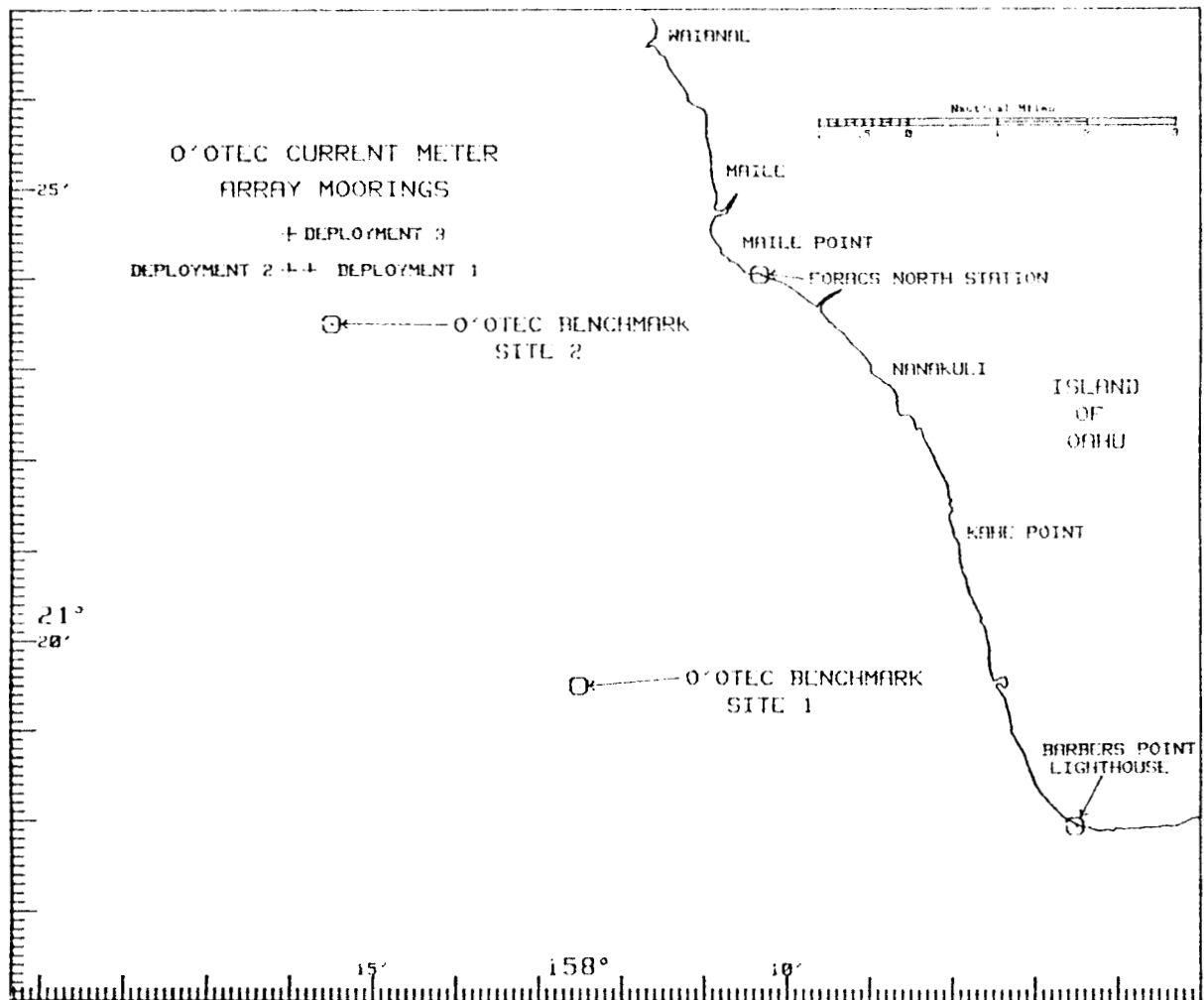
Figure 13.--Kahe Point, Oahu OTEC benchmark and current meter
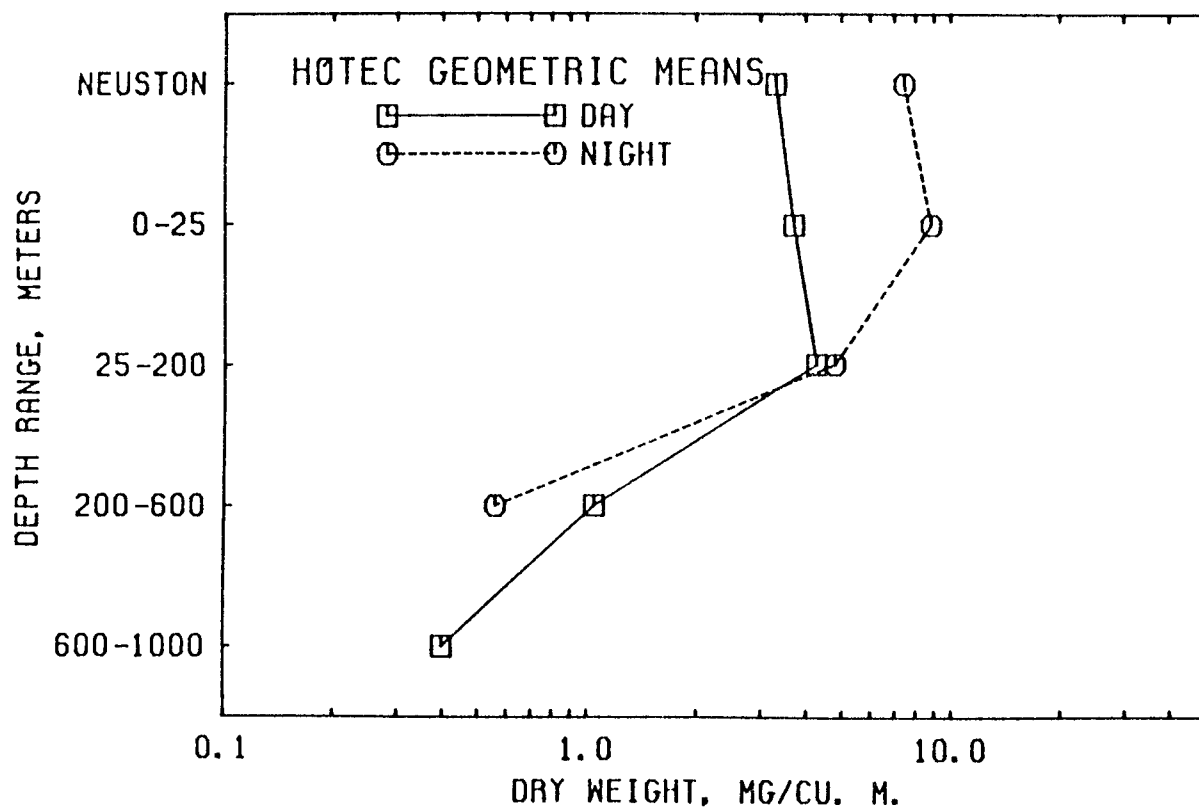mooring sites, designated the O'OTEC sites (Noda et al. 1981b).

Figure 14.—Geometric means of zooplankton dry weight versus depth for HOTEC cruises 11 and 12, day and night (Noda et al. 1981a).
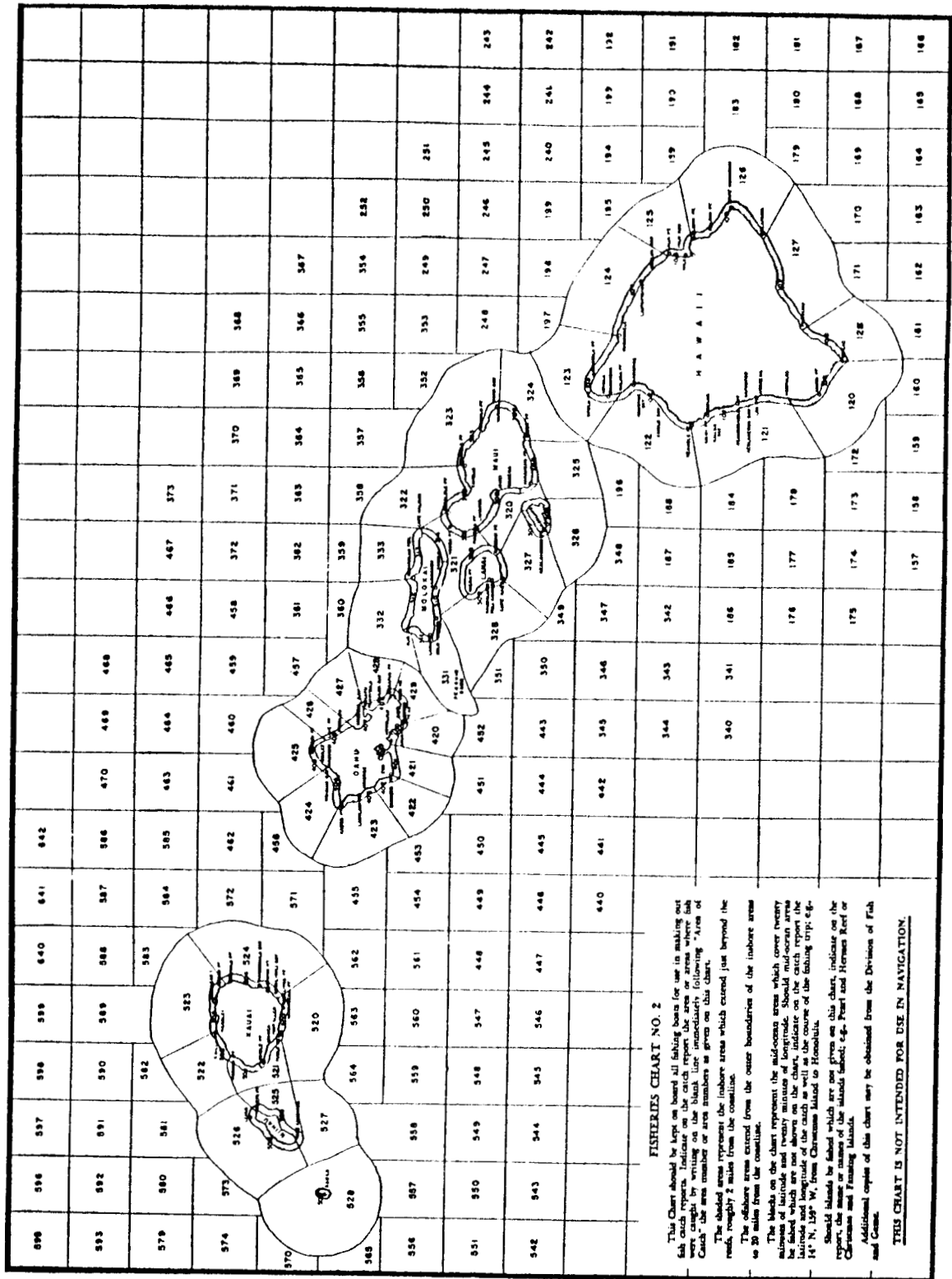
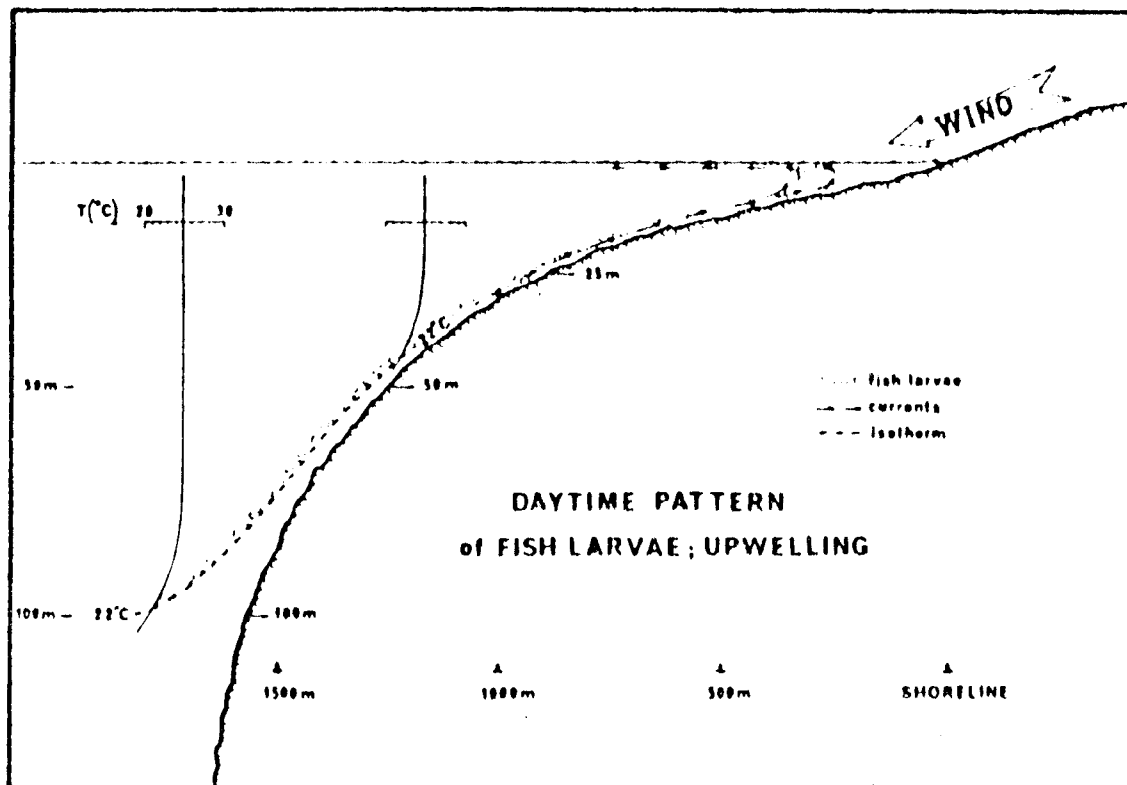Figure 15.--Fisheries Chart No. 2.

Figure 16.--Hypothetical daytime patterns of fish larvae off Kahe Point, Oahu, during upwelling. Temperature profiles from BT records 15 March 1974, 1500-1530 h H.S.T. Abcissal numbers are distances (m) from shoreline (Miller 1979).